Heterogeneous Integration of Shape Memory Alloys for High-Performance Microvalves

HENRIK GRADIN

Doctoral Thesis in Microsystem Technology
Stockholm, Sweden 2012

TRITA-EE 2012:014
ISSN 1653-5146
ISBN 978-91-7501-304-6

www.kth.se
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Front cover pictures:
Left: Scanning electron microscope (SEM) image of a 1 × 3.3 mm² Shape Memory Alloy (SMA) actuated gas microvalve in its open state.
Right: Photograph of a 1.8 × 4.5 mm² silicon SMA-wire actuator in a hot actuated state.
Abstract

This thesis presents methods for fabricating MicroElectroMechanical System (MEMS) actuators and high-flow gas microvalves using wafer-level integration of Shape Memory Alloys (SMAs) in the form of wires and sheets.

The work output per volume of SMA actuators exceeds that of other microactuation mechanisms, such as electrostatic, magnetic and piezoelectric actuation, by more than an order of magnitude, making SMA actuators highly promising for applications requiring high forces and large displacements. The use of SMAs in MEMS has so far been limited, partially due to a lack of cost efficient and reliable wafer-level integration approaches. This thesis presents new methods for wafer-level integration of nickel-titanium SMA sheets and wires. For SMA sheets, a technique for the integration of patterned SMA sheets to silicon wafers using gold-silicon eutectic bonding is demonstrated. A method for selective release of gold-silicon eutectically bonded microstructures by localized electrochemical etching, is also presented. For SMA wires, alignment and placement of NiTi wires is demonstrated for both a manual approach, using specially built wire frame tools, and a semi-automatic approach, using a commercially available wire bonder. Methods for fixing wires to wafers using either polymers, nickel electroplating or mechanical silicon clamps are also shown. Nickel electroplating offers the most promising permanent fixing technique, since both a strong mechanical and good electrical connection to the wire is achieved during the same process step. Resistively heated microactuators are also fabricated by integrating prestrained SMA wires onto silicon cantilevers. These microactuators exhibit displacements that are among the highest yet reported. The actuators also feature a relatively low power consumption and high reliability during long-term cycling.

New designs for gas microvalves are presented and valves using both SMA sheets and SMA wires for actuation are fabricated. The SMA-sheet microvalve exhibits a pneumatic performance per footprint area, three times higher than that of previous microvalves. The SMA-wire-actuated microvalve also allows control of high gas flows and in addition, offers benefits of low-voltage actuation and low overall power consumption.

Keywords: Microelectromechanical systems, MEMS, silicon, wafer-level, integration, heterogeneous integration, wafer bonding, Au-Si, eutectic bonding, release etching, electrochemical etching, microvalves, microactuators, shape memory alloy, SMA, NiTinol, TiNi, NiTi, cold-state reset, bias spring, gate valves, wire bonding

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KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden
Sammanfattning

Denna avhandling presenterar metoder för att tillverka aktuator i mikroelektromekaniska system (MEMS) och mikroventiler för höga gasflöden genom integrering av minnesmetaller (SMA) i form av trådar och folier på kiselskivor.


Nya konstruktioner för gasmikroventiler är presenterade och ventiler med både SMA-folier och SMA-trådar är tillverkade. SMA-foliemikroventilen visade en pneumatisk prestanda per yta som är tre gånger högre än tidigare mikroventiler. SMA-trådsventilen uppsås även den en hög flödeskontroll och därutöver också aktivering vid låg spänning och en låg total effektförbrukning.
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List of Publications

The thesis is based on the following international journal papers:


7. "A low power high flow SMA wire gas microvalve", H. Gradin, D. Clausi, S. Braun, G. Stemme, J. Peirs, W. van der Wijngaart and D. Reynaerts *IOP Journal of Micromechanics and Microengineering*, accepted for publication
The contribution of Henrik Gradin to the different publications:

1. major part of design, all fabrication and experiments, part of writing
2. major part of design, fabrication, part of experiments, major part of writing
3. major part of design, fabrication and experiments, part of writing
4. major part of design and fabrication, part of experiments and writing
5. part of design, fabrication, experiments and writing
6. major part of design, all fabrication and experiments, major part of writing
7. major part of design, fabrications, experiments and writing

The work has also been presented at the following international conferences:


Chapter 1

Introduction

There is an ongoing demand for more powerful, efficient and cheaper tools and machines. MicroElectroMechanical Systems (MEMS), also referred to as micromachines in Japan and Micro Systems Technology (MST) in Europe, offer a promising rapid technological evolution, similar to how the Integrated Circuit (IC) industry has revolutionized our lives.

MEMS generally refers to devices that are up to a few millimeters in size and include components with sizes from 1 to 100 µm (1 µm = 0.001 mm). While an IC can be viewed as a brain that processes information, MEMS components can be seen as eyes and arms that interact with the environment, sensing and manipulating it, respectively. Examples of MEMS devices available today include pressure sensors, inkjet printer heads, accelerometers, switches, grippers and pumps. MEMS devices are already employed in cars, cell phones and medical devices, but an increasing number of devices and applications using MEMS are emerging in the market. Thus MEMS have a rapidly expanding role in today’s society.

The goal of developing MEMS devices is to create smaller, cheaper and more efficient devices and machines compared to their conventional macro-sized counterparts. In addition, since MEMS devices operate at the microscale, different physical forces dominate than at the macroscale, which can be exploited. For example, the surface area to volume ratio is much larger at the microscale compared to the macroscale and forces such as gravity are negligible compared to friction and capillary forces. A cube with a side length of 1 meter has an area to volume ratio of \((6 \times 1) \text{ m}^2/1 \text{ m}^3 = 6/\text{m}\). This can be compared to a cube with a side length of 1 µm which has a ratio of \((6 \times 1) \text{ µm}^2/1 \text{ µm}^3 = 6 000 000/\text{m}\).

The MEMS industry started as an evolution of the IC industry and still uses many of the latter’s fabrication techniques and materials. In order to develop the MEMS technology further, with new applications and devices with better performance, new materials need to be utilized. However, introduction of these new materials poses several challenges since standard manufacturing techniques can seldom be applied directly to them. Therefore, to process such new materials...
and achieve low fabrication costs, new fabrication techniques need to be developed.

This thesis presents new research in the field of MEMS. One high-performance material of interest in MEMS is the Shape Memory Alloy (SMA). This thesis focuses on ways to integrate this material into silicon MEMS in a batch manufacturable fashion. The aim of the research was to create high-performance SMA actuators that could be used to manufacture small microvalves capable of controlling high flows and pressures.

The structure of the thesis is as follows:

Chapter 2 presents existing actuator types in MEMS and introduces SMA as a material together with its properties and possible use in MEMS.

Chapter 3 gives an overview of different integration approaches used in MEMS and presents solutions for integrating SMAs.

Chapter 4 combines the information from the two previous chapters and demonstrates how to create SMA silicon microactuators with large deflections.

Chapter 5 introduces microvalves as an application for SMA microactuators and demonstrates SMA gas microvalves with large flow rate control.

Chapter 6 finally summarises the work in this thesis.
Chapter 2

Microactuation and Shape Memory Alloys

This chapter presents different microactuation principles and introduces shape memory alloys (SMAs). The material properties of SMAs and their potential use as actuator materials in MEMS are also covered.

2.1 MEMS actuation

An actuator is a mechanical device that converts energy input into mechanical work and motion. Usually the input energy is in the form of an electrical signal, but it can also be in the form of pneumatic pressure or thermal heat. An actuator forms also an important complement to sensors, which work in the opposite way by detecting a physical variable in the environment and converting it to an electrical signal. Actuators can enable movement, manipulation and control of substances and objects in the environment, whereas sensors can register the type and quantity of the substances or objects.

Many different types of actuation mechanisms exist. In MEMS, actuators can be classified as electrostatic, piezoelectric, thermal and magnetic actuators, depending on the physical principle they operate under [1]. Table 2.1 lists some of these actuation principles.

Microactuators can be fabricated by either transferring conventional macroactuators to the microscale or utilizing relatively new actuation principles, e.g., piezoelectric and SMA actuation, which have only recently had substantial progress in their technology implementation [2,3]. When downscaling macroactuators to the microscale, some actuation mechanisms have associated advantages, such as less material usage, faster response time and lower power consumption. On the other hand, problems may also arise, e.g., the large frictional forces that impede rotating motors on the microscale.
Table 2.1: Common microactuation principles [4] and typical maximum work densities [5].

<table>
<thead>
<tr>
<th>Actuation type</th>
<th>Principle</th>
<th>Work density (J/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrostatic</td>
<td>Electrically charged objects attract or repel each other</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>An applied voltage generates a material deformation</td>
<td>$1 \times 10^5$</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Electromagnetic and/or permanent magnetic field interaction causes motion</td>
<td>$4 \times 10^5$</td>
</tr>
<tr>
<td>Thermal</td>
<td>Thermal expansion or solid-liquid phase change create motion</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td>SMA</td>
<td>Thermal actuation with a crystal phase transformation occurring in the solid state</td>
<td>$2 \times 10^7$</td>
</tr>
</tbody>
</table>

Depending on the application, some actuation principles are more suited than others. The criteria for selecting the most appropriate actuation principle requires consideration of the achievable maximum force, maximum displacement, displacement resolution, actuation frequency, power efficiency and lifetime. In addition, such properties scale differently, depending on the actuation principle, and thus the size of the actuator needs to be taken into account.

When comparing different microactuators, their work density is of interest, i.e. how much work output they can produce divided by the volume of the actuator. The work density determines the maximum force and displacement that actuator can achieve relative to its size. Table 2.1 compares typical maximum work densities for different actuation principles. In the table, SMA actuators are included as a separate type. SMA actuators can be classified as thermal actuators, but instead of thermal expansion or a solid-liquid phase change when heated, crystal reorganization occurs while the material remains solid. Since SMAs offer much higher work densities compared to other actuation principles, SMAs are particularly interesting materials for use in microactuators that require high forces and large displacements. The work presented in this thesis focuses on SMA as MEMS actuator material.

### 2.2 Shape Memory Alloys

Shape Memory Alloys (SMAs) are materials that have the ability to remember their shape. SMAs can exist in two stable states. At low temperatures, the SMA is in the martensitic phase, also referred to as the cold state. In this state, the SMA is easily bent or stretched and will retain the deformed shape even after the deforming stress has been removed. At high temperatures, the material is in the austenitic phase, also referred to as the hot state, which is a robust state where the material
is hard to bend and stretch. If an SMA is initially deformed in the cold state and then heated to the hot state, the initial shape can be recovered, as if it has been remembered. This transformation is also referred to as the Shape Memory Effect (SME) and is schematically illustrated in Figure 2.1. The first indication of these material properties was obtained in 1932 when Ölander observed rubber-like behavior in an AuCd alloy [6, 7]. Twenty years later, the shape memory effect was identified and such properties were observed in many other alloy systems [7]. However, it was only following Buehler’s discovery in 1962 that NiTi alloys had shape-memory properties that a strong interest in SMAs arose [8, 9]. This material was named Nitinol (Nickel Titanium Naval Ordnance Laboratory) and it was shown to have superior SMA properties compared to the previously discovered materials. Today, many alloys have been found to exhibit the shape-memory effect, e.g., Ni-based, Cu-based and Fe-based alloys. In addition, polymers such as PTFE (polytetrafluoroethylene), ceramics such as ZrO₂ and biological systems such as bacteriophages, can have shape-memory properties [2, 10].

The main SMA used commercially today is still the NiTi alloy. The benefits of this alloy compared to other SMAs include higher working stresses and strains, higher stability in cyclic applications, biocompatibility and higher electrical resistivity, which makes electrical actuation simpler [11, 12]. The use of NiTi shape memory alloys are currently used for a broad range of applications including flexible eye glass frames, stents inserted into humans and movement of solar panels in space applications.

The material properties of a NiTi-based alloy in its two different states can be illustrated by the stress-strain relation shown in Figure 2.2. In the martensitic state, the plateau corresponds to conditions where the SMA is easily deformed with a relatively small increase in stress. This can be contrasted with the rigid austenitic state where the stress increases almost linearly with an increase in strain. The stress-strain curves can however have large variations, not only depending on the composition of the alloy but also on the thermo-mechanical history of the material and the mode of deformation: compression, tension or torsion [13]. Table 2.2 lists...
CHAPTER 2. MICROACTUATION AND SHAPE MEMORY ALLOYS

Figure 2.2: Schematic of stress-strain curves of a NiTi-10%Cu alloy in the hot austenitic and cold martensitic states [13].

Table 2.2: Material properties of Ni-Ti shape memory alloys [14]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus Austenite</td>
<td>≈83 GPa</td>
</tr>
<tr>
<td>Young's Modulus Martensite</td>
<td>≈28–41 GPa</td>
</tr>
<tr>
<td>Yield Strength Austenite</td>
<td>195–690 MPa</td>
</tr>
<tr>
<td>Yield Strength Martensite</td>
<td>70–140 MPa</td>
</tr>
</tbody>
</table>

some typical values for the properties of NiTi SMA.

The temperature at which the phase transformation between austenite and martensite occurs in SMAs can be chosen to be in the range from −150 to 200 °C, mainly depending on the material composition [11]. In the case of NiTi, a temperature range of around −100 to 100 °C (Ms, as defined below) can be achieved by tuning the atomic percentage of Ni from 51% to 49% in the alloy [13]. To achieve the desired transformation temperature, very accurate control of the material composition is therefore needed, resulting in a non-trivial manufacturing of the alloys.

SMAs also display hysteresis behavior during temperature-induced transformation. Four characteristic temperatures of the material can be defined. The temperature where the material starts to transform during heating is known as the austenite start temperature (As) and the transformation is complete at the austenite finish temperature (Af). Similarly, during cooling the martensite start (Ms) and finish (Mf) temperatures correspond to the start and completion of the transformation, respectively. These temperatures are indicated in Figure 2.3 together with typical temperature ranges in which the transformation occurs [11].

The transformation of SMAs between the austenitic and martensitic states can occur in a combination of three different basic ways [2,11]. These three different
2.2. SHAPE MEMORY ALLOYS

Figure 2.3: Schematic of hysteresis during the phase change from martensite to austenite as a function of temperature. The temperatures for austenite start ($A_s$), austenite finish ($A_f$), martensite start ($M_s$) and martensite finish ($M_f$) is indicated together with common temperature intervals [11].

shape memory effects are illustrated in Figure 2.4.

The first effect is the so-called "One-way effect" and is illustrated in Figure 2.4a. In this effect, the material is first deformed by an external load, and after the load is removed, the material remains deformed. Upon heating, the original shape prior to deformation is recovered.

The second effect, known as the "Two-way effect", is shown in Figure 2.4b. This involves the material "remembering" two shapes. Here, no external forces are needed. Instead, a cold shape is remembered in addition to the hot state. The memory of a cold state that is different from the hot shape can only be obtained after specific thermomechanical treatment of the material, which is referred to as training [15,16].

Figure 2.4c illustrates the third shape memory effect, namely superelasticity or pseudoelasticity [2,13]. This effect is only present at temperatures of a few tens of degrees higher than $A_f$ and limited to a few tens of degrees above it [11]. The phase transformation to martensite is induced by a deforming load instead of a temperature change. When the load is removed, the material reverts back to austenite and recovers its shape.

A better understanding of the working principle of the shape memory effect can be gained by studying the crystal structure of an SMA (Figure 2.5). In the austenite state, also known as the parent phase, the crystal can be viewed as having a square lattice. When the austenite state is cooled to martensite, the structure transforms from a square lattice to an alternating tilted rhombus-based lattice. This transformation occurs without a shape or volume change on the macroscopic scale. This phase is commonly referred to as self-accommodated or twinned martensite.
CHAPTER 2. MICROACTUATION AND SHAPE MEMORY ALLOYS

Figure 2.4: The three different Shape Memory Effects: (a) one-way memory effect, (b) two-way memory effect, and (c) superelasticity effect, represented macroscopically as a deformed spring on the left. The change in length (L), load (F) and temperature (T) for each cycle are illustrated in the graphs on the right [11].
2.3. POTENTIAL USE OF SMAS IN MEMS

Figure 2.5: Schematic of SMA crystal structure in the one-way effect [13]. The two-way effect and the pseudoelasticity occur between the austenitic phase and the detwinned martensitic phase [2].

When the twinned martensite is deformed, more and more twin boundaries migrate until the material is completely detwinned. On the macroscopic scale, this is observed as a shape change. Upon heating, the lattice returns to its square parent shape, which only exist in one configuration, and thus the original shape of the material is recovered [13].

2.3 Potential use of SMAs in MEMS

Because of their large work density, SMAs are of particular interest for use in MEMS applications. In addition, macroscopic disadvantages of SMAs, such as high power consumption and low heat transfer rates, become less pronounced at the microscale [2]. Nevertheless, the maximum actuation frequency at the microscale is limited to tens of Hertz, in contrast to electrostatic actuators, which can reach tens of MHz [1]. Table 2.3 lists some additional advantages and disadvantages of utilizing SMAs for microactuation.

Fabrication of MEMS is often cost driven. NiTi SMAs are commercially available in bulk form as sheets, tubes and wires. In 2011, the market prices of NiTi sheets was around 200 € for 30 µm thick sheets with dimensions 100 × 100 mm² for quantities of more than 10 sheets, which equates to a cost of 2 €/cm² [17]. The cost of NiTi wires was around 3 €/m for 38 µm diameter wire and quantities less than 100 m or 1 € for quantities larger than 1000 m [18]. Usually, wires are not placed closer than 10 wires/cm, which results in a cost of 0.3 €/cm² for low quantities. For a typical MEMS process with one lithography step and one Deep
Table 2.3: Advantages and disadvantages of SMA microactuation [2,11].

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>High energy density</td>
<td>Low Efficiency</td>
</tr>
<tr>
<td>Electrical actuation at low voltages</td>
<td>High power consumption</td>
</tr>
<tr>
<td>High reliability</td>
<td>Degradation and fatigue effects</td>
</tr>
<tr>
<td>Noise-free operation</td>
<td>Long response time</td>
</tr>
<tr>
<td>Variety of shape changes</td>
<td>Operation in a limited temperature range</td>
</tr>
<tr>
<td>Simple designs</td>
<td></td>
</tr>
<tr>
<td>Biocompatibility</td>
<td></td>
</tr>
</tbody>
</table>

Reactive Ion Etching (DRIE) step, the cost is around 3 €/cm² (estimated cost by a MEMS foundry for a device fabrication quotation in 2009). The material cost of NiTi sheets are thus not significantly higher than the costs of other parts required in a regular MEMS fabrication process, and the cost of wires is almost negligible.

Even though SMAs have very interesting properties and would be ideal for microactuation, their use in MEMS has been limited so far, mainly because of a lack of reliable and cost-efficient integration approaches. This thesis therefore focuses on new methods of integrating NiTi sheets and NiTi wires for the creation of microactuators with high performance. These actuators can then be used in several applications, e.g., to construct high performance microvalves, which will be presented in the following chapters.
Chapter 3

Heterogeneous Integration

This chapter describes methods for fabricating MEMS devices with advanced materials. The focus lies on the heterogeneous integration and utilization of SMAs in MEMS and presents complete approaches for integrating SMA sheets and SMA wires on silicon wafers.

3.1 Introduction

To progress MEMS technology further, advanced materials not commonly used in the IC industry are needed to enable high-performance devices and functionalities that would otherwise not be possible. Often these new materials and components are not compatible with existing fabrication processes. New integration technologies are therefore needed to take advantage of these new materials while achieving low fabrication cost.

Three ways of integrating and combining materials and subsystems in the MEMS industry are: monolithic integration, where the whole device is manufactured from one substrate, hybrid integration, where two substrates are produced separately and in the end combined at chip-level, and heterogeneous integration, where two substrates are combined on wafer-level [19]. Figure 3.1 shows a schematic of these three integration approaches in the context of this thesis.

Monolithic integration

Wafer-level monolithic integration is the most commonly used micromachining technique. In this approach, the MEMS material is first deposited onto the main substrate (Figure 3.1a). Examples of deposition techniques include sputter deposition, evaporation, chemical vapor deposition (CVD) and electroplating [20]. The deposited material is then processed together with the main underlying substrate. The whole fabrication takes place on one substrate, which is diced into individual chips in the final step. This method is however limited in the design
Figure 3.1: Simplified schematic of (a) wafer-level monolithic integration by surface machining, (b) chip-level hybrid integration, and (c) wafer-level heterogeneous integration in relation to the work described in this thesis. Typically, the bottom substrate is a regular silicon wafer and the top substrate is the new material to be integrated.
of the device, the available fabrication processes and available materials due to incompatibilities, e.g., process temperature and etching methods for the different materials and components [19, 21].

In the case of SMAs, both sputtering and evaporation of SMA films directly onto the MEMS structure have been demonstrated [5, 22, 23]. This approach allows batch-compatible processing. The process is however complicated since precise control of the material composition is needed [24] and post-deposition annealing temperatures are typically above 450 °C [5], which limits the use of many materials and processes. In addition, since NiTi is a difficult material to machine [24], damage to the substrate can occur during machining or when using harsh etchants. NiTiCu-based film deposition has been reported for layers up to 30 µm [25]. An example of a microgripper constructed using NiTiCu SMA thin-film deposition is shown in Figure 3.2.

Figure 3.2: Microgripper fabricated by monolithic integration of SMA thin films [5, 23, 26].

**Hybrid integration**

To overcome limitations of process and material incompatibilities, chip-level hybrid integration may be an option. In this method, the two components are first manufactured on separate substrates and after dicing, the components are assembled together, typically using a pick-and-place approach (Figure 3.1b). An example of a device fabricated using this integration approach is a MEMS component and an IC chip combined in a single package [19]. Disadvantages of this method are that device miniaturization and the number of electrical interconnects between the chips are limited [19].

For integrating SMAs, hybrid integration is a common method. Here, the SMA and the MEMS device are first fabricated separately. The two are then combined, usually by a pick-and-place approach for each device [2, 27]. The advantage of this method is that commercially available robust bulk SMA, available in a wide range of thicknesses, can be used with no need for complicated deposition control and
CHAPTER 3. HETEROGENEOUS INTEGRATION

Figure 3.3: Hybrid integration with pick and place of an SMA film and other components for the creation of a microvalve [27].

annealing processes. However, a disadvantage is that the pick-and-place method on chip-level is a serial process and can be cumbersome and fairly expensive. Figure 3.3 illustrates an SMA microvalve, showing how the individually fabricated components are assembled [27].

Heterogeneous integration

Heterogeneous integration technologies combine the advantages of monolithic and chip-level hybrid integration technologies by using wafer-level processing but with less limitations to certain processes than for the case of monolithic integration [19]. An example of heterogeneous integration is when two substrates are first processed separately with different technologies and instead of dicing both substrates into individual chips, as in hybrid integration, the two substrates are combined substrate-to-substrate or chip-to-substrate (Figure 3.1c). After the integration step, post processing is also possible, e.g., to produce high density electrical interconnects. As a final step, the substrate is diced into individual chips. Heterogeneous integration can allow the manufacture of complex microsystems that are not possible to fabricate with conventional micromanufacturing techniques [19]. In addition, when the process can be divided into stages that can be individually optimized at a substrate level, there is a potential to lower the cost of fabrication compared to monolithic integration [28].

It is only very recently that heterogeneous integration of SMAs into MEMS has been reported. Approaches for heterogeneous integration of SMA sheets and SMA wires will be presented later in this chapter.

One key component of heterogeneous integration approaches is the utilization of different bonding techniques, which will be introduced in the following sections.

When employing heterogeneous integration on a substrate-to-substrate level, all of the structures need to be connected on both substrates to enable handling, i.e.
individual structures can not be singulated before the integration step, as illustrated in Figure 3.1c(1). This can be achieved by either directly connecting the structures or employing a temporary handle substrate. Following the integration step, this support needs to be removed. This requirement can introduce additional challenges and different solutions to this will be presented in Section 3.4.

3.2 Wafer-bonding techniques

Bonding two substrates together is an important MEMS fabrication technique that enables the construction of complex three-dimensional (3D) components. Typically, when combining two substrates, high pressures and temperatures are applied while the substrates are in contact. Usually, at least one of the substrates is a silicon wafer. A schematic of a wafer-bonding process is shown in Figure 3.4. The integration often takes place in a special wafer-bonding machine, which can apply a controlled heat and pressure load while the substrates are kept under vacuum to avoid air being trapped between them. A wide variety of wafer-bonding techniques exist, and the most common are listed in Table 3.1 on the next page [29].

The bonding methods listed have different advantages and disadvantages, making them more or less suited for different applications. When it comes to wafer-level heterogeneous integration, direct bonding of the materials is usually not a suitable method, and bonding methods with intermediate layers are required. Often adhesive bonding is utilized for heterogeneous integration because of the relatively low temperatures that are needed and the fact that the method works with virtually any substrate material [29]. In this thesis, the use of non-adhesive heterogeneous integration approaches will also be introduced for the integration of SMA sheets and wires onto silicon wafers.

Figure 3.4: Schematic of a wafer-bonding process with an intermediate layer, in which force and heat are applied to fuse the two substrates together.
<table>
<thead>
<tr>
<th>Bonding Method</th>
<th>Heat and pressure cause plastic deformation and fusion of two substrates. Typically, at least one surface contains a metal.</th>
<th>High bond pressure + hermetic + compatible with electronic wafers - very high net forces for full wafer bonding required - limited temperature stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocompression bonding and direct metal-to-metal bonding</td>
<td>Heat and pressure cause plastic deformation and fusion of two substrates. Typically, at least one surface contains a metal.</td>
<td>High bond pressure + hermetic + compatible with electronic wafers - very high net forces for full wafer bonding required - limited temperature stability</td>
</tr>
<tr>
<td>Ultrasonic bonding</td>
<td>Similar to thermocompression bonding but heat is generated by ultrasonics. A common method used for wire bonding, which is described in more detail in the next section.</td>
<td>Room temperature to 250°C + compatible with electronic wafers - only demonstrated for small bond areas</td>
</tr>
<tr>
<td>Low-temperature melting glass bonding</td>
<td>An inorganic low-temperature melting glass is deposited on the substrates and used as an intermediate bonding material.</td>
<td>Low to moderate bond pressure + high bond strength + hermetic + bond temperatures that are not always compatible with electronic wafers</td>
</tr>
<tr>
<td>Adhesive bonding</td>
<td>An adhesive material, commonly a polymer, is applied as the intermediate bonding layer.</td>
<td>Room temperature up to 400°C + high bond strength + low bond pressure + works with practically any substrate material, including electronic wafers</td>
</tr>
</tbody>
</table>

- **Room temperature** to 400°C
- **High to moderate bond pressure**
- **High bond strength**
- **Low bond pressure**
- **Works with practically any substrate material, including electronic wafers**
- **Not always compatible with electronic wafers**
- **Limited temperature stability**

- **350−600°C**
- **High bond pressure**
- **Hermetic**
- **Compatible with electronic wafers**

- **400−1100°C**
- **Low to moderate bond pressure**
- **High bond strength**
- **Hermetic**
- **Bond temperatures that are not always compatible with electronic wafers**

- **Room temperature to 250°C**
- **Compatible with electronic wafers**
- **Only demonstrated for small bond areas**
- **No hermetic bonds**
- **Limited temperature stability**
<table>
<thead>
<tr>
<th>Wafer-bonding technique</th>
<th>Principle</th>
<th>Typical conditions</th>
<th>Advantages and disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct bonding</td>
<td>Direct contact of two wafers and spontaneous bonding. Careful cleaning prior to contact and moderate bond pressures are required.</td>
<td>200 − 400 °C</td>
<td>+ high bond strength, + good bond quality, + compatible with electronic wafers, - sensitive to native oxides at surfaces.</td>
</tr>
<tr>
<td>Anodic bonding</td>
<td>Joining of a wafer with a noble metal and a wafer with an alkali-containing glass under a high voltage and elevated temperature. Also referred to as field-assisted bonding.</td>
<td>150 − 1500 V, 200 − 500 °C</td>
<td>+ high bond strength, + hermetic, + compatible with electronic wafers, - bond temperature together with high voltage is not always compatible with electronic wafers.</td>
</tr>
<tr>
<td>Solder bonding</td>
<td>Metal or metal alloy used as intermediate bonding layers. Wafers with a metal layer are brought into contact and heated above the melting temperature.</td>
<td>Low bond pressure, 150 − 450 °C</td>
<td>+ high bond strength, + hermetic, + compatible with electronic wafers, - solder flux.</td>
</tr>
<tr>
<td>Eutectic bonding</td>
<td>A variant of solder bonding where a combination of some materials results in a low melting point liquid eutectic that can be used for joining two wafers. Common combinations are Au and Si. Discussed further in the following sections.</td>
<td>Low to moderate bond pressure, 200 − 400 °C</td>
<td>+ high bond strength, + hermetic, + compatible with electronic wafers, - sensitive to native oxides at surfaces.</td>
</tr>
</tbody>
</table>

Table 3.1: Commonly used wafer-bonding techniques [29]
3.3 Wire bonding

When integration involves wires or when wires can be used instead of material sheets, fully automatic cost-efficient wire bonding tools offer a convenient, fast and cheap way of both aligning and fixing the wires to the substrate. Wire bonding is a mature back-end process for producing electrical interconnects for chip packaging in the IC industry. Modern production wire-bonding tools can bond wires with speeds of up to 22 bonds per second and placement accuracies of better than $2.5 \mu m$ [30]. The use of wire bonders for MEMS fabrication has only recently started to be explored.

The attachment of a standard bond wire to a bond pad is similar to a welding process. The energy input for the welding process is a combination of force, temperature and ultrasonics. Figure 3.5 illustrates the most common wire-bonding approach, known as the ball/stitch bond process, for connecting a gold wire to a gold or aluminum pad.

![Figure 3.5](image)

Figure 3.5: Schematic of a standard thermosonic ball/stitch bonding of a wire. (a) A gold wire is fed through a ceramic bond capillary and an electrical flame off (EFO) melts the wire to form a gold sphere, known as the free air ball (FAB), at the end of the wire. (b) The tool presses the FAB with a defined force against a heated pad. (c) Together with simultaneous input of ultrasonic energy, the weld between the ball and pad is generated. (d) The tool then moves towards the second bond pad. (e) Here, a stitch bond is performed by compressing the wire between the capillary tip and the pad. With force, ultrasonics and heat, the weld between the wire and pad is created. (f) The tool then moves up to a certain height where the wire is torn off, and (g) the process can start over again (Paper 5).

Automatic wire bonding is an emerging technology for MEMS fabrication. By adapting the wire-bonding process, a variety of complex MEMS devices can be produced by taking advantage of the fast and accurate wire placement. An illustrative example of a complex MEMS structure that can be produced with these machines are micro coils as illustrated in Figure 3.6 [31].

The existing wire-bonding technology is limited to certain material combinations, and typically a soft wire material is used for the wire that is deformed and welded onto the bond pad since material failures are more likely for hard wire materials [32]. Common wire-bond pad material combinations include are Au-Au, Au-Cu, Au-Pd, Al-Au and Al-Ni. NiTi SMA wires, on the other hand, are very
3.4. BOND AND RELEASE PROCESSES

Figure 3.6: Micro coils generated with a wire bonder by winding a wire around SU-8 posts [31].

hard to deform [33]. In this thesis, wire integration approaches for NiTi based on a modified ball/stitch bonding process will be presented.

3.4 Bond and release processes

After two substrates have been bonded or materials integrated, the substrates or materials usually need to be separated from each other locally at several locations, e.g., to allow movement of an actuator. The connection between the two substrates is either through the bonding layer or is in-plane with the structures on the sides. Four different approaches for separating bonded parts are presented in Figure 3.7.

In the first approach, all structures are bonded and the moving structures are released at a later stage of the fabrication process by removing the underlying bonding layer (Fig. 3.7a). This method is based on wafer-bonding methods with intermediate bonding layers that can be sacrificially etched with high selectivity. Examples of such intermediate bonding materials are silicon dioxide [34] and polymers [29,35]. This method also includes sacrificial etching of the buried oxide layer in SOI (silicon on insulator) wafers. In general, there are two restrictions on sacrificial underetching. First, when underetching large structures, the whole substrate is exposed to the etchant for a long time, which may result in destruction of the device in harsh chemical environments, such as hydrofluoric (HF) acid used for etching oxide sacrificial layers. Second, the width of the structures to be released by underetching must be considerably smaller than the width of the structures required to remain bonded, otherwise all structures will be underetched and released.

Both issues are usually addressed by integrating etch holes in the structures to be underetched (Figure 3.7b). These etch holes drastically minimize the distance to underetch, which results in shorter exposure to harsh chemicals and the possibility
Figure 3.7: Illustration of different bond and release methods: (a) bonding and sacrificial underetching without etch holes, with a footprint area determining selectivity; (b) bonding and sacrificial underetching with etch holes, allowing selective release of structures depending on the etch-hole pitch; (c) bonding and localized removal of the bonding layer only underneath the structure to be released; and (d) localized bonding and release by removal of a support structure (Paper 1).
of underetching structures with a larger footprint area than the structures to remain bonded. However, the etch holes potentially decrease the mechanical stability and performance of the device. Furthermore, the fabrication of such etch holes is feasible only for structures consisting of thin layers, such as thin silicon layers, e.g., in micromirror arrays [36]. If the moving structures are hundreds of micrometer thick, etch holes are difficult to fabricate with the required aspect ratio.

A technique for releasing structures without additional etch holes involves the localized removal of the bonding layer (Figure 3.7c). An example of a localized removal method is the localized laser ablation of polymer-bonding layers [37]. For bonding technologies based on metal intermediate layers, an alternative and flexible approach is based on electrochemical etching of the intermediate metal layer in a neutral salt solution. This principle has been shown for surface micromachined structures on aluminum layers [38]. In this thesis, a method for sacrificial etching of metallic wafer-bonding layers is presented. Here, Au-Si eutectic bonding layers are locally removed by electrochemical etching in a neutral salt solution. A detailed description of this process can be found in Paper 1.

Another approach to achieve structures where some parts are bonded and others not is to utilize selective or localized bonding (Figure 3.7d). Localized bonding between two substrates can be obtained by either modifying the interface material prior to bonding, to define bonding and non-bonding areas, or by localized heat on the desired areas of the bond interface during bonding. Examples of patterned bond interface layers include adhesive layers applied only on areas where bonding is desired [39] and bond blocking layers, such as gold or platinum, defining local nonbonding areas in anodic bonding [40]. Examples of local heat triggering approaches include integrated heaters for both localized eutectic and silicon fusion bonding [41], localized soldering using inductive heating [42] as well as local heating using lasers [43].

To enable localized bonding on wafer-level, a temporary handling substrate or mechanical connections between all structures are needed. The removal of the mechanical support structures can be achieved through dicing or controlled fracture [44, 45]. However, such break-away structures limit the design freedom, potentially increasing the footprint area of the device. Dicing also has a lower accuracy than typical MEMS etching processes, and thus potentially, remnants of the support may be left that can limit the device performance and moving structures may be damaged while removing the support. However, this approach does not require chemical etching, which is beneficial as a bonded device usually consists of many different materials and is therefore likely to be sensitive to a large number of chemicals. In addition, with the right layout of the support, the final device-dicing step can also be used to remove the support. Localized bonding and removal of the support in the same step as dicing of the individual chips is described in Paper 2 for the removal of connections between SMA actuators in sheets, in Paper 6 for the release of a microvalves’ free-moving gate, and in Papers 3, 4, 7 for the cutting and separation of locally bonded SMA wires.


3.5 Wafer-level SMA-sheet integration

SMA sheets are commercially available in a wide range of thicknesses and sizes, with NiTi being the most commonly used material [17]. SMA sheets can be machined into almost any shape, which allows a large flexibility in the design. Common machining approaches of SMA sheets include electrochemical etching, laser cutting and chemical etching in a mixed solution of hydrofluoric and nitric acid [24]. Usually, the SMA sheet is machined before integration to a MEMS structure to prevent damage to the structure during the harsh SMA machining processes. Heterogeneous integration of SMA sheets has only recently been reported. One approach involves patterning and selective transfer by laser ablation of an SMA sheet onto polymer microvalve structures [46]. The advantage of this method is that components with different sizes can be combined, e.g., small actuators and large valve housings. However, this approach still resembles a hybrid integration approach since separate components are being added such as spacers and membranes with bonding foils (similar to Figure 3.3). A separate study successfully integrated SMA sheets onto plastic substrates using microriveting by electroplating [47,48]. However the riveting occupied a large area (2.5 × 3.5 mm²) and has not yet been demonstrated in a full batch process. Figure 3.8 illustrates this process for a patterned SMA sheet before and after the plating riveting process.

![Figure 3.8: SMA integration by Cu-electroplated 'riveting' on a polyimide substrate with (a) the patterned SMA before integration, and (b) after integration. The target application is a wireless actuated microgripper [47].](image)

To develop a wafer-level heterogeneous integration approach, a whole SMA sheet needs to be transferred at once. This has been demonstrated by adhesive bonding of a fully patterned NiTi SMA sheet onto a patterned silicon wafer [49]. The adhesive used in this process was BCB (benzocyclobutene), which was stamped onto the silicon structure before bonding. However, the bond strength of this process for SMAs under high strain cycling has not been investigated. In addition, the stamping process was complicated and the bond-layer thickness was difficult to control. High reflow during curing can also result in unwanted bonding of moving parts in the MEMS structure. One solution is to use photocurable BCB, which can...
3.5. WAFER-LEVEL SMA-SHEET INTEGRATION

Flexures to reduce thermal stress when bonding

Patterned SMA sheet
Machined silicon wafer
SMA sheet bonded to silicon wafer

Figure 3.9: Images of a patterned SMA sheet and silicon wafer before integration (left) and the final wafer after gold silicon eutectic integration (right) together with the corresponding cross-sectional representation (Papers 2 and 6).

be patterned. However, this results in a smaller process window for the integration and potentially lower bond strength [39].

An alternative approach of integrating full SMA sheets to silicon microstructures without the use of polymers is to use Au-Si eutectic bonding. In this approach, a mixture of gold and silicon forms a liquid above 363 °C, which allows bonding of two substrates [50]. However, large thermal stresses occur when bonding materials with different thermal expansion at elevated temperature. One way to reduce the thermal stress is to create springs between the SMA structures that are to be bonded. The springs can easily accommodate the stress created during bonding and can be, e.g., fabricated at the same time as the machining of the SMA to create actuators. Spring structures have successfully been shown to reduce stress in adhesive bonding of SMA sheets [49].

Since the bond region is defined by the gold and silicon areas, it is relatively easy to define bond regions by patterning the gold in iodine-based etchants. It is usually sufficient to pattern just the gold on the SMA or the gold on the silicon surface since reaction with the oxide on silicon or the SMA is limited.

A patterned SMA sheet with defined Au area bonds and a machined silicon wafer with Au on can be seen in Figure 3.9. The wafer is subsequently aligned to the patterned SMA and bonded at 400 °C under vacuum in a wafer bonder.
The resulting bonds exhibit very high bond strengths. It is important to have a gold layer thickness of more than 1 µm to ensure a bond yield of greater than 90%. Even though using springs between the SMA shapes decreases the stress, there are still huge stresses in the bond interface, which can result in cracks in the silicon. To limit the risk of cracks in the bond interface, a small bond area is needed. It is not feasible to bond areas larger than $1 \times 1 \text{ mm}^2$ without cracks appearing in the bulk silicon because of the thermal mismatch of the materials.

A more detailed description of this process and investigation of optimal bond parameters can be found in the attached Paper 2. This method will further be discussed with regard to fabrication of SMA-sheet actuators in Chapter 4.5 and microvalves in Chapter 5.3 and attached Paper 6.

### 3.6 Wafer-level SMA-wire integration

SMA in the form of wires can also be utilized in MEMS components. The integration approach is very different to sheet integration. SMA wires are available with a wide range of dimensions, from 25 to 500 µm in diameter [18].

The use of SMA wires for actuation in MEMS has so far been limited since an efficient batch integration approach has not yet been developed. To date, SMA wires in MEMS have been integrated by pick-and-place approaches and are typically in the form of coils and springs [51,52]. To reduce the cost of SMA-wire integration, batch and wafer-level fabrication approaches are needed.

For wafer-level integration of SMA wires, the integration process can be divided into two steps. The first step concerns the alignment of the wires to the wafer and their placement. This is henceforth referred to as global fixation. This step only needs to keep the wires in place for additional wafer processing, and thus can be temporary fixation. Ideally, the fixation should be on the edge of the wafer so as not to occupy valuable space for the chips. Wafer-level fixation is illustrated in Figure 3.10.

The second step involves permanent fixation of the wires on every chip to create devices, such as SMA-silicon actuators. This is henceforth referred to as local fixation. Three important criteria should be fulfilled in this step. Firstly, because fixation occurs on the MEMS chip, it should occupy a small space to decrease the fabrication cost per chip. Secondly, the fixation needs to be very strong to cope with the high forces that the SMA produces. Thirdly, the integration should preferably allow electrical connection directly to the SMA wires. The fixation of the SMA wires will be discussed in this chapter and electrical connections will be discussed in the subsequent chapter.

Often when integrating SMA wires, it is desirable to integrate a prestrained wire for the creation of an actuator. (Described in detail in Chapter 4.6.) The temperature of the integration therefore needs to be below the phase transformation temperature of the SMA. This further complicates and limits the integration process. Typical NiTi wires have a transformation temperature around 90 °C.
3.6. WAFER-LEVEL SMA-WIRE INTEGRATION

Figure 3.10: Schematic of a wafer with SMA wires (black lines) fixed at the wafer edges (grey circles). This is here referred to as global or wafer-level fixation. The devices or chips are illustrated as dotted square. The wire is then fixed on every chip (grey squares). This is here referred to as the local or chip-level fixation.

Wafer-level placement

When heterogeneously integrating wires onto silicon wafers, the silicon wafer is often structured first. The wires then need to be aligned accurately to these silicon structures to create the functional device, such as an actuator.

One possible approach to the placement of the wires is to first place the wires in a holding frame. The wires can then be positioned with a well-controlled pitch that matches the pitch of the structures on the silicon wafer. In this frame, the wires can also be pretrained with a well-defined strain for all wires. The wire frame can then be aligned to the structures on the wafer. One solution for fixing the wires to the wafer is to use an adhesive. After the wires have been attached to the wafer, they are released from the frame, e.g., by simply cutting them. Figure 3.11 illustrates how a frame with wires can be aligned to a silicon wafer and Figure 3.12 shows a photograph of a dedicated wire frame and wafer integration stage. A full process for embedding NiTi wires into SU-8 is presented in detail in Paper 3.

However, the above approach has a number of disadvantages. Firstly, a dedicated frame is needed to hold the wires in place. Secondly, the wires must be placed manually or a method for the automatic placement of wires in the frame needs to be developed. Thirdly, alignment of the wire frame to the silicon structures either needs to be done coarsely by hand or specialized alignment tools need to be constructed. In addition, the fixing with adhesive needs to be performed manually, or if a photo-curable polymer is used, the stage needs to be built to fit into a mask.
CHAPTER 3. HETEROGENEOUS INTEGRATION

Figure 3.11: Cross-section schematic of a dedicated stage for the placement of SMA wires on a silicon wafer (Paper 3).

Figure 3.12: Photograph of a dedicated wire frame and wafer-integration stage with SMA wires integrated in a polymer on a silicon wafer (Paper 3).

aligner or a course manual UV curing process can be used.

An alternative approach is to use a commercially available wire bonder that allows placement of the wires one at a time with high accuracy and speed. For SMA wires, NiTi is the most commonly used material, but due to its hardness [33], it is not feasible to use standard wire-bonding techniques, such as ball/stitch bonding described in Chapter 3.3. Instead, mechanical fixation of the wire is needed. This fixation can be performed by first machining a silicon wafer with an anchoring structure and a clamp structure. The wire is then mechanically fixed to the wafer as illustrated in Figure 3.13. This wafer-level placement method is described in
3.6. WAFER-LEVEL SMA-WIRE INTEGRATION

Figure 3.13: Cross-sectional view of SMA-wire integration using a wire bonder (top), with the corresponding 3D close-up illustration and scanning electron microscope (SEM) images of the result. In the process, a free air ball is first generated by an electrical discharge (a). The ball is then hooked into an anchoring structure machined in the silicon wafer. The SMA wire (37.5 μm diameter) is fed and guided over the entire wafer area to its second fixation structure (b). The SMA wire is then clamped between machined silicon cantilevers and is finally cut off by truncating the wire using the bond capillary and a high bond force (c) (Paper 5).

By using wire bonding, very accurate placement of wires can be achieved with current commercially available tools. Since heating of the wire is localized during the electrical flame-off process, it is also possible to directly integrate prestrained wires, which are commercially available. However, the disadvantage of this approach is that the silicon wafer needs to be first machined to host the anchoring and clamping structures. This occupies valuable space on the wafer and might introduce additional fabrication limitations or challenges in the MEMS-device manufacturing process. The development of small hook-in and clamping structures together with the possibility of fabricating them at the same time as creating the MEMS-device structures without additional process steps, will increase the potential of this technology further.

Device fixation

After the wires have been aligned and placed on the wafer, it is possible to attach them to each separate device. Three different approaches for device fixation will be presented in this thesis.

One way of fixing the SMA wires at chip level is to use adhesives. A good method for carrying this out on a wafer-level with good alignment and resolution is
standard lithography with polymers. Figure 3.14 presents a process-flow scheme of the main steps in this approach. After wafer-level placement of the wire, spinning of the polymer onto the wafer at low speed is possible. However, a uniform coverage of polymer is often difficult to achieve. One solution is to first spin the polymer onto the wafer (Figure 3.14b), followed by the wafer-level insertion of the wires and then lamination of an additional polymer layer on top of the wires (Figure 3.14c). The polymer can subsequently be locally cured in a standard mask aligner, precisely defining the anchor points of the wire on every chip (Figure 3.14d). As a final step, the wires can be cut in-between the devices at the same time as the individual chips are diced out, creating individual wire pieces for every chip (Figure 3.14f). If a polymer-fixation technique is used also for the wafer-level placement, instead of removing the uncured polymer and applying new layers for device fixation, the same layer can be used twice: first, low resolution curing is performed for the wafer-level placement followed by higher resolution curing in a mask aligner for device fixation. If prestrained wires are used, it is important that the curing temperature of the polymer is below the phase transformation of the wire. This limits the combination of SMA-wire types and polymers that can be used together. This process is described in detail in Paper 3 for the case where SU-8 is used for the fixation of the wires.

One disadvantage of polymer fixation is the difficulty of exposing material underneath the wire, creating problems with fully curing the polymer or removing the resist in the case of negative or positive resists, respectively. Exposure
3.6. WAFER-LEVEL SMA-WIRE INTEGRATION

underneath the wire is essential for reliable fixation and can potentially be achieved by employing highly light-reflecting layers on the sides and underneath the wires. Another disadvantage of non-conductive polymer fixation is the need for an additional process step after fixation to achieve electrical connections to the wires.

An alternative approach to using polymers is therefore metallic fixation of the wire. The main benefit is that an electrical connection to the wire can be achieved in the same process step as mechanical fixation. Because relatively thick metal layers are needed to fully embed SMA wires (typically 38 µm in diameter), metal plating is a good method. The fabrication in this case is initially similar to the polymer-fixation method, but instead of creating a polymer fixation anchor, a polymer mold is created. Since the mold is just temporary and does not need to hold the wires in place in the end, the lithography step is less sensitive compared to permanent polymer fixation. The plating then takes place in the molds. Once again, for prestrained wires it is important to use a low process temperature during plating.

Paper 4 present in detail a process for Ni electroplating to fixate NiTi SMA wires. The resulting bond strength is excellent with this method and the wire itself is the first to break when evaluating the bond in shear tests. Figure 3.15 shows an SEM image of an embedded SMA wire and the homogenous Ni plating around it.

Device-level fixation with Ni-electroplating is a very promising solution. However, for a complete back-end process, it is desirable to also perform the local chip-level fixation with in a wire bonder. Anchoring and clamping wires at chip-level, in a similar fashion to wafer-level methods, may be feasible but limit the design freedom of the MEMS device itself since silicon clamps and anchors need to be constructed on it. In addition, these clamps and anchors occupy a relatively large area compared to metal-plated structures. The size of the anchors is limited by the wire-bonder capillary and cannot be made much smaller. Clamps can be made smaller but not too small since the length of the clamp governs the strength of fixation. In addition, it is desired to make the electrical contacts at the same time as the integration. This can be achieved by coating the anchor and clamp

![Figure 3.15: SEM image of a cross-section of an integrated SMA wire with a uniformly electroplated Ni anchor surrounding the wire (Paper 4).](image-url)
with a metal before integration.

An alternative approach to fixing the wire at chip level with a wire bonder is to use so-called wire-bonder bumping. In this approach, a metal ball formed by the electrical flame off is pressed against the surface of a substrate, deforming the ball. The ball that is "bumped" should be made of a very soft material so that it will deform around the wire and fix it. Gold bumps are therefore well suited for this purpose. Since deformation of the ball is limited, one bump is often not sufficient to embed the whole wire, which is typically more than $25 \mu m$ in diameter. The wire therefore needs to be placed in a recess before being fixed by bumping on top of the wire. This recess can be fabricated by either etching the silicon, metal-plating or first placing gold bumps on each side of the wire. An initial test of this method was performed and an SEM image of the resulting substrate is shown in Figure 3.16 [53]. The factors affecting the fixation strength and formation of different recesses are still under evaluation.

### 3.7 Discussion and outlook

For SMA-sheet integration, Au-Si eutectic bonding is a promising approach, which has been demonstrated to generate a very strong bond and a yield of more than 90%. However, the risk of cracks due to large thermal mismatches of materials...
requires further investigation to determine whether cracks are reduced for small bond areas. Further, the use of amorphous silicon for the eutectic bonding should be investigated. Another possible solution to decrease thermal stresses is to perform local Au-Si eutectic bonding \([41]\), in which only the bond region is heated. Interesting alternatives for SMA-sheet integration include the use of low temperature (<100 °C) patternable adhesives \([54]\), which are locally applied at the bond area together with an adhesion promoter for NiTi, or mechanical clamping, e.g., using electroplated rivets. A process for mechanical fixing could be realized by first patterning the SMA sheet, then temporarily fixing it to the wafer with adhesives and finally performing the electroplate-riveting process. These methods are particularly interesting for future research projects on wafer-level SMA-sheet integration.

For SMA wires, the most promising permanent integration method at chip level is electroplating. The achievable bond strength relative to the area occupied would be difficult to match with other methods since a metal bond that fully embeds the wire is formed during the electroplating process. The creation of the plating mold by spinning resist onto the wafer may be problematic with deep-etched structures but can likely be solved by employing spray coating and/or lamination of resist sheets onto the wafer. The main challenge with SMA-wire integration is still the temporary global wafer-level placement of the wires. To automate the wire placement process, wire-bonding tools offer the most promising solution. However, the use of anchor and clamp fixation structures on the wafer is questionable since they occupy valuable space on the wafer and more importantly, can limit the design freedom of the MEMS device and complicate the fabrication because of the additional specialized fabrication steps required. The area occupied by the fixation structures can be lowered by only having one anchor and one clamp on every wafer, and then winding the wire around pillars, with a minimal footprint, for each row of wires. To circumvent the above-mentioned limitations of the fabrication, either the fixation structures must be adapted to fit into the process flow of the fabricated MEMS devices, or the wires need to be automatically placed in a separate wire frame and then the frame aligned to the wafer containing the MEMS devices. A 4” wafer with MEMS devices can, for example, be aligned to a machined 6” wafer that acts as both carrier and wire frame. However, the alignment of the wafer to the carrier and the reusability of the carrier need to be studied further.

Ideally, the integration process would only require a wire bonder for both the global wafer-level and local chip-level integration process. However, it is likely that the bond strength of the local fixation, for the same occupied footprint area, would be much lower and the electrical-contact resistance higher than fixing the wire by electroplating. It would be interesting to continue the research on ball-bumping fixation of the wires to assess whether the resulting bond strength can come close to that achievable with electroplating fixation. If the above challenges can be solved, the complete SMA-wire integration process could be developed as a back-end process.

Another possible integration approach for SMA wires, which was beyond the...
scope of the work described in this thesis, is to completely embed the SMA wires in a polymer matrix. This polymer matrix could then be treated as a sheet, which can be aligned and laminated onto a silicon wafer. Lamination could either be the final step, resulting in permanent fixation, or used to generate plating molds for electroplating.
Chapter 4

SMA MEMS Actuators

This chapter describes approaches utilizing SMAs for creating MEMS actuators. For a full actuator, it is not sufficient to merely integrate the material onto silicon. Cold-state reset mechanisms, to deform the material in the martensitic state, and triggering of the phase transformation by integrated heating are also needed.

4.1 Introduction

SMA actuators can be fabricated that utilize either the one-way effect or the two-way effect (Chapter 2.2). However, most actuators utilize the one-way effect. Reasons for this are two-way effect actuators offer lower strains (typically, the maximum value for single actuation of NiTi is 2% vs. 8%), lower forces, lower cycling stability and require training compared to one-way effect actuators [55,56].

In the one-way effect, three different types of shape recovery are possible when an SMA transforms from a deformed martensitic state to the austenitic phase (Figure 4.1) [2,11,57]. If the SMA is allowed to recover freely, it can recover its initial shape and generate motion as no load is acting on it (Figure 4.1a). If instead the SMA is constrained during the phase transformation, no motion will occur, but a strong force will be exerted on the surroundings (Figure 4.1b). A third scenario occurs when the SMA acts against an external force. In this case, a counteracting force and motion are generated during the phase transformation, resulting in work production (Figure 4.1c). When the SMA is cooled, it is once again deformed by the external force. Repeated heating and cooling will result in cyclic motion.

Work production against a counteracting force is the most interesting case for the creation of an actuator that can be cycled. To construct this type of actuator, a deforming load firstly needs to be integrated with the SMA. This is commonly referred to as a cold-state reset mechanism. Secondly, repeated heating and cooling of the SMA is needed to drive the phase transformations. These two fabrication requirements will be discussed in the following sections.
4.2 Cold-state reset

Cold-state reset mechanisms refer to methods for deforming the SMA in the cold state to achieve cyclic operation of the SMA actuator. These mechanisms can also be referred to as bias mechanisms. Cold-state reset mechanisms can be divided into intrinsic and extrinsic methods [58]. Intrinsic methods involve modifying the whole or part of the SMA material crystal structure to create two states. One common intrinsic method is to train the SMA to achieve the two-way Shape Memory Effect (Chapter 2.2). This is achieved by thermomechanical cycling of the material to create oriented defects [58]. Other intrinsic methods include local annealing of the SMA by laser or direct Joule heating [59]. Local annealing is a common method used together with monolithic integration of SMAs (Chapter 3.1).

In contrast, in extrinsic methods, an external element is coupled to the SMA to provide the cold-state deformation. Loading of the SMA to induce the cold-state reset can be performed in several ways. Figure 4.2 illustrates some common ways of loading an SMA wire and the many possible configurations that exist.

Integration of cold-state reset mechanisms is often difficult to implement at the microscale [58]. Typical cold-state reset mechanisms employed in previous SMA microactuators include mechanical obstructions, antagonistic designs and material layers with built-in stress. Mechanical obstructions are often integrated during assembly of the SMA element and the MEMS structure [2] and is common in hybrid integration approaches (Chapter 3.1). Material layers with built-in...
stress are common in monolithic integration processes, where stress in the SMA can be generated during the annealing step after deposition of the material. A counteracting silicon beam can then, for example, be used to create a bimorph actuator [26]. However, material stacks with different stress only allow for bending motion of the actuator.

When designing cold-state reset mechanisms, it is important that the reset force is not too high to achieve low recovery stress and a large number of actuation cycles.

4.3 Heating and cooling

The second important design aspect for SMA actuators concerns the method for heating and cooling the SMA to induce the phase transformations. It is possible to both heat and cool the material by changing the environment temperature. However, this results in a poor actuator response time and low energy efficiency as the surroundings also need to change temperature. The most common approach is therefore to integrate a heating element on the actuator itself and utilize the environment as the cooling supply.

For integrated heating, the SMA can be heated either directly or indirectly. In the direct heating method, a current is passed through the SMA, increasing its temperature and triggering the phase transformation. This is also referred to as resistive or Joule heating. The temperature increase is related to the resistance
of the SMA and the current [60]. To avoid the need for high currents, the SMA should have a high resistance. Thin long wires or thin SMA beams are ideal for this type of heating. In addition, a closed current path is needed for this type of heating, limiting the shape that the SMA can adopt. To ensure direct electrical connections, any oxide on the SMA, which is common in the case of NiTi, also needs to be removed [24].

An alternative way of heating is through indirect heating. In this approach, an external element is heated and heat generated is transferred to the SMA. The easiest way of indirect heating is using an external heating source, e.g., a hot plate separate from the MEMS component. However, it is preferable for the heating element to be integrated directly on the actuator, and a common way to achieve this is to construct a resistive heater on the SMA. An advantage of this type of heating is that the shape of the SMA can take almost any form, and the heater can be designed to heat the SMA evenly. However, disadvantages of this method are the additional fabrication steps needed to create the heater and the requirement of an insulation layer on top of the SMA to prevent the heater short-circuiting. In addition, a larger power is required compared to direct heating of the SMA. Wireless indirect heating of SMAs has also been reported, in which an external RF (radio frequency) magnetic field is coupled to an inductor-capacitor (LC) circuit which heats the SMA at the electrical resonance frequency of the circuit [47,48].

Cooling of the SMA, in both the external and internal heating methods is usually allowed to occur passively by convection to the surroundings and conduction through the substrate on which the SMA resides. However, if the SMA actuator is to operate at high frequencies, active cooling is needed. An example of a method for active cooling SMAs is the use of a gas flow over the SMA, which can easily be achieved in microvalve applications. This will be discussed further in Chapter 5.

### 4.4 Design parameters

When designing SMA actuators, two additional important factors need to be taken into account. Firstly, depending on how the SMA is deformed, the energy efficiency and energy density of the SMA varies. Three types of load case (tension, torsion and bending) are compared in Table 4.1.

Tension is by far the most efficient way of utilizing the SMA. However, sometimes

<table>
<thead>
<tr>
<th>Load type</th>
<th>Energy efficiency (%)</th>
<th>Energy density (J/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>1.3</td>
<td>466</td>
</tr>
<tr>
<td>Torsion</td>
<td>0.23</td>
<td>82</td>
</tr>
<tr>
<td>Bending</td>
<td>0.013</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 4.1: Comparison of the energy efficiency, conversion of heat into mechanical work, and corresponding energy density under different types of load for SMAs [11].
Table 4.2: Relation between target number of cycles and maximum-allowed strain and stress for NiTi alloys [11].

<table>
<thead>
<tr>
<th>Cycles</th>
<th>Max. strain (%)</th>
<th>Max. stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>500</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>275</td>
</tr>
<tr>
<td>100000+</td>
<td>1</td>
<td>70</td>
</tr>
</tbody>
</table>

The relation between target number of cycles and maximum-allowed strain and stress for NiTi alloys is shown in Table 4.2. Tension of the SMA is difficult to implement, e.g., in a sheet. Therefore, the other modes of operation are important to allow different types of actuator design. For example, thick SMA sheets in MEMS are typically operated in a bending mode and can deliver both a large displacement and large force [2].

SMAs also experience fatigue related to the stresses, strains and temperatures it operates under [61–63]. The maximum stress and strain that the SMA can operate under in relation to the target number of cycles of the SMA actuator are listed in Table 4.2 for NiTi alloys.

In the next two sections, an actuator design based on SMA sheets operating in bending mode and an SMA-wire actuator working in tensile mode will be presented. Torsion-mode actuators were not investigated in this thesis.

### 4.5 SMA-sheet actuators

In the case of SMA-sheet actuators, bending is the most natural mode of operation in MEMS. Even though tensioning is more efficient than bending, it is difficult to subject a full sheet to pure tension. Application of the torsion mode requires rotational motion, and it is less obvious on how to utilize it for MEMS actuation. The bending mode, often coupled with some tension, has so far been the most common mode of operation for SMA sheets in MEMS [58]. Both a cold-state reset mechanism and heating mechanism are needed to manufacture a full SMA-sheet actuator. The bending motion of the actuator can be achieved either out of plane, i.e., upward and downward relative to the sheet plane, or in plane, i.e., part of the SMA material is removed and the SMA can move in the sheet plane. Typically, SMA grippers are constructed with in-plane movement. An example of an in-plane gripper formed from an SMA sheet is illustrated in Figure 4.3. However, for in-plane movement, a large part of the SMA material is wasted and a thick SMA sheet is needed to ensure high mechanical strength. The rest of this thesis will focus on out-of-plane SMA-sheet actuators.

For an out-of-plane SMA sheet actuator, the cold-state reset mechanism can be introduced before, during or after the integration step of the SMA sheet. The three different approaches are presented in Figure 4.4. When the sheet is integrated heterogeneously on a wafer-level, alignment between the patterned SMA sheet and
Figure 4.3: SEM image of a micro-gripper for sub-millimeter lens handling. The fabrication process flow is illustrated to the right, showing that the desired shape is laser cut (1) and then thermomechanically cycled under constraint (training process) (2). The working principle is shown in (3) [58].

the patterned substrate is needed. Such alignment is preferably carried out using commercially available bond aligners. In the first case (Figure 4.4a), when the cold-state reset is created on the SMA before the integration step, the alignment step is difficult since the cold-state SMA is not straight. The alignment therefore has to be performed when the SMA is in its flat hot state or a balancing reset mechanism needs to introduced that is removed after integration, i.e., balancing stress layers. Bond alignment at elevated temperatures is not a standardized process, and balancing stress layers can be difficult to remove at the end of the fabrication. Thus, it usually better to create the reset mechanism after integration.

The second approach is to create the cold-state reset during the integration process (Figure 4.4b). This is a common method in pick-and-place approaches, in which a mechanical spacer deforms the SMA [2,27]. For heterogeneous integration on a silicon wafer, the mechanical spacer can be formed by structuring the bulk silicon or by creating an elevation on the wafer, e.g., in polymer. However, structuring of the bulk silicon wafer needs to result in a relatively flat silicon surface to bond to, which can be difficult without utilizing SOI (silicon on insulator) wafers. During the alignment, care must also be taken to keep the two substrates separated until completely aligned, otherwise the topologies of the two wafers are at risk of being scratched and hooked into each other. This process could be feasible with careful planning but was not investigated further in this thesis.

In the third approach, the cold-state reset is created after integration of the SMA. This method allows the use of standard bond and alignment tools since
4.5. **SMA-SHEET ACTUATORS**

![Diagram](image)

Figure 4.4: Examples of cold-state reset mechanism integration for out-of-plane bending SMA-sheet actuators. The cold-state reset can be created before (a), during (b) or after (c) the heterogeneous integration step. (The SMA is illustrated in black and the substrate in white.)

Both substrates are flat before and during the integration. This method has been demonstrated successfully with BCB bonding and by applying stress layers on the SMA after integration [49]. Aluminum, silicon dioxide and silicon nitride have all been investigated. It is also possible to apply an external force to deform the SMA in the cold state after integration. One such approach is discussed in Chapter 5.3 and Paper 6 for the creation of a microvalve where the supplied pressure is used to deform the SMA.

Regarding heating, both direct and indirect heating are possible. For direct heating, the SMA sheet needs to be patterned to form a current loop [2]. This however, weakens the actuator itself. Another option is to split the SMA into different regions, where one is directly heated and another performs the work [47]. In this way, the heat can be transferred to the working part without weakening the actuator itself. The disadvantage of this approach is that more space is consumed.

Indirect heating is therefore better suited for SMA-sheet actuators since no patterning of the sheet is required and the SMA shape can be freely designed for the application. The heater can be placed on top of the actuator itself, without any increase in footprint area. If a resistive heater is used, care needs to be taken to create a good electrically insulating layer between the SMA and the
4.6 SMA-wire actuators

For SMA-wire actuators, tensioning of the wires is the best and most efficient mode of operation (Table 4.1). Bending of the wires is also feasible, and the corresponding integration approach can then be similar to sheet integration. However, bending of a wire will provide very low work output compared to bending of a sheet. Torsion of a wire can also be performed, but rotation of a single wire end can be difficult to implement in MEMS. Wire tensioning is therefore the most appropriate approach for the fabrication of SMA-wire microactuators.

A good way of creating tension, is to employ a counteracting spring connected to the wire. The wire first needs to be prestrained before being connected to the spring structure. Upon the first actuation, the wire contracts, and at the same time tensions the spring. Upon cooling of the wire, the spring relaxes and the wire is tensioned again. Cycling can then be generated by repeated heating and cooling of
4.6. SMA-WIRE ACTUATORS

Figure 4.6: Fabrication and operation of an SMA-wire actuator based on wire tension: (a) The wire is prestrained; (b) The wire is integrated onto a silicon beam, which acts as a counteracting spring for the cold-state reset of the wire; (c) In the hot state, contraction of the wire causes the silicon beam to bend (Papers 3 and 4).

The design and operation of this actuator is presented in detail in Paper 3. A theoretical model to estimate the deflection of this type of SMA actuator is shown in Figure 4.7. The deflections and stroke are related to the prestrain value of the SMA wire, \( \epsilon_{\text{sma},0} \), and the geometrical factor \( G \), which is a design parameter:

\[
G = \frac{b \cdot t^3}{12 \cdot n \cdot A_{\text{sma}} \cdot e^2} \tag{4.1}
\]

where \( b \) and \( t \) are the width and thickness of the silicon cantilevers, respectively, \( n \) is the number of wires, \( A_{\text{sma}} \) is the cross-sectional area of each wire and \( e \) is the prestrain value.

Figure 4.7: Plot of theoretical design model for SMA wire actuators for a specific prestrain value \( \epsilon_{\text{sma},0} \) (Paper 3).
distance between the wires and the silicon cantilevers. In this way, the actuator can be designed for a specific stroke.

Heating of the SMA wires can be performed indirectly, e.g., by means of a resistive heater on top of the wire. However, when wires of small dimensions are used, such as 37.5 µm in the present study, direct heating offers considerable benefits since the resistance is high and fabrication of heaters on top of such small wires is difficult. Direct heating requires a closed current path. If the forward current is conducted through a wire, the reverse current can be conducted through another wire or through the silicon spring if high conductive silicon is used. Figure 4.8 depicts an SMA-wire actuator with two wires forming the closed current path, which are attached to a silicon cantilever with two beams. The wires are connected through nickel-plated anchors as described in Chapter 3.6. This
4.7 Discussion and outlook

When comparing the SMA-wire and SMA-sheet actuators, the wire actuator has so far demonstrated the most promising actuator properties. The benefits of the wire actuator over the sheet actuator are that it can be operated in the most efficient mode, i.e., tension, and heating of the wire is direct, lowering the power needed for transformation compared to indirect heating. One disadvantage of the wire actuator is that the integration of wire materials in MEMS is not a standard process.

Even though the processing of sheets in MEMS is more closely related to wafer processing, the main challenges to creating a comparable SMA actuator are optimization of the external heating mechanism and the need for good control over actuator exhibits out-of-plane motion but in-plane actuators are also feasible to build. Photographs of a fabricated actuator in the cold and hot state, respectively, are shown in Figure 4.9.

The SMA wire actuator demonstrates excellent performance and long time stability. A deflection graph of an actuator for 150,000 cycles is shown in Figure 4.10. The actuator can switch state at a frequency of 1 Hz (limited by the cooling rate) and requires a power of 70 mW. Further characterization of this actuator is presented in Paper 4. Since the resistance of the actuator changes with the deflection (discussed in Paper 4), analog control of the actuator is also feasible [64] instead of the conventional SMA on/off operation in the cold and hot state, respectively.

One possible application for an actuator with high deflection is microvalves, which will be discussed in the next chapter.

Figure 4.10: Long-time cycling of an SMA-wire, actuator demonstrating the excellent deflection and long-term stability characteristics (Paper 4).
the deposition and stability of stress layers to allow the creation of a bimorph actuator. Alternatively, the cold-state reset mechanism can be provided by a mechanical obstruction which deforms the SMA during integration, avoiding the complex stress layer deposition altogether. These fabrication alternatives should be the focus of further research to continue the development of SMA-sheet actuators.

Improvements and variations to the design of SMA-wire actuators are also possible. For example, different designs based on in-plane actuators with a single wire and the reverse current conducted via the silicon spring, may be feasible. Variation of the number of wires and wire dimensions provides scope for tuning the voltage and current needed for actuation. However, current SMA-wire actuators already offer excellent performance, long-term cycling stability and fabrication invariance over the wafer. In its current state, the SMA-wire actuator is a very promising candidate for many applications demanding high stroke actuation. The actuator is among the MEMS actuators with the highest reported displacements as illustrated in Figure 4.11 [1].

![Figure 4.11: Comparison of the maximum displacement and frequency of different types of microactuators, including the SMA-wire actuator presented in this thesis [1].](image)
Chapter 5

Microvalves

The following chapter covers gas microvalves. Different types of microvalves and operation principles are first introduced. Finally, new designs of SMA microvalves with high performance are presented and compared to previous work.

5.1 Introduction

Gas-control components, such as gas valves, are fundamental building blocks in the automation and automotive industry. MEMS can potentially enable the cost-efficient batch fabrication of microvalves with small sizes, rapid response time and low power consumption. Over the years, many different types of microvalves have been designed and fabricated [65,66]. However, to gain a foothold in the market, MEMS microvalves have to compete effectively with the mature technology of conventional valves. Primarily due to a poor performance versus cost relationship compared to traditional gas valves, microvalves are not yet used as standard components in industry. This thesis attempts to addresses this shortcoming by presenting high-performance, large gas-flow-control valves that can be batch manufactured with a small footprint area, and therefore potentially lower cost.

Since gas microvalves typically operate under high pressures and large flow rates are desired, a strong and robust actuator that can generate large displacements is required. SMAs are excellent candidates for satisfying these criteria, and their use in microvalves will be discussed in detail here.

5.2 Microvalve designs

Two main microfluidic designs for active mechanical gas microvalves exist [67]. The traditional valve designs are the so-called seat or diaphragm valves. In this design, a boss or diaphragm moves towards or away from a flow orifice, and thereby closes or opens the valve (Figure 5.1a).
Figure 5.1: Illustration of the working principle of a seat/diaphragm valve (a), where the flow regulating boss moves against the flow/pressure, and a gate valve (b), where the gate moves perpendicular to the flow.

An alternative microvalve design is the gate-valve design, where the flow is regulated by a sliding gate moving perpendicular to the flow (Figure 5.1b). The main advantage of gate valves is that they allow a higher gas flow control compared to seat valves, but have the limitation of leakage flow in the closed state.

**Seat microvalves**

Many different active MEMS seat microvalves have been fabricated using different actuation mechanisms, such as magnetic, electric, piezoelectric and thermal [65,66]. Some of the high flow seat valves are presented and compared later in Table 5.3. Since the pressure of the gas is acting directly on the boss of the seat valve, very strong actuators are needed for high pressure applications. SMAs are well suited for this task and have been used in many seat microvalves demonstrating high pressure and flow control [2, 27, 46–86]. One very recent design is shown in Figure 5.2. However, to improve the operation under very high pressures, pressure-balancing schemes need to be introduced [87, 88]. An example of a pressure-balanced microvalve is illustrated in Figure 5.3.

The main controlling parameter that determines the maximum flow that can
5.2. MICROVALVE DESIGNS

Figure 5.2: Example of a bistable SMA seat microvalve with magnetostatic latches. (a) Schematic cross section of the closed, switching and open state of the valve; and (b) A photograph of the bidirectional SMA microactuator [86].

Figure 5.3: Example of a pressure-balanced microvalve with electrostatic actuation: (a) cross-sectional illustration, and (b) resulting forces related to the dimensions inside the valve [87].

pass through the microvalve is the deflection of the actuator. For this reason, SMA is again a good choice of material, but to achieve even higher flows, nozzle/seat optimization needs to be performed with the aim of increasing the area around the valve orifice [89–91]. The creation of multiple small nozzles instead of one large one can be achieved without increasing the total chip area of the valve.
An example of a multi-nozzle gas microvalve with SMA actuation is illustrated in Figure 5.4. In this design, the multiple nozzles provide an increased flow output. The valve consists of a bottom and top silicon substrate combined with an SMA ring that is deformed during assembly by silicon springs. Upon heating the valve, the SMA transforms and the valves opens. However, development of this multi-nozzle valve was stopped at the design stage due to lack of funding.

**Gate microvalves**

In gate valves, a gate moves perpendicular to the flow. In the fully open state, the gate is completely retracted from the flow orifice and does not obstruct the flow path as in seat valves. This type of design generally allows much larger open-state flow rates compared to seat valve designs of similar sizes. An additional advantage of gate valves is that the actuator does not need to counteract the full gas pressure during closure since the gate movement is perpendicular to the flow. There is however one major drawback with gate microvalves. Since frictional forces are comparably large at the microscale, friction between sliding structures creates significant technical problems. To circumvent the friction, a space is needed between the flow channel orifice and the gate. However, this introduces leakage in the closed state. This limitation does not exist with seat-valve designs, where the boss can move in contact with the surrounding orifice with virtually no leakage flow.

However, many valve applications can tolerate a certain degree of leakage flow, making the gate-valve design highly attractive for large flow and high pressure applications. One such application consists of two gate valves coupled in series in a 3/2-way pressure controller, which can be used as a so-called current to pressure or I/P converter. An I/P converter converts an electrical signal into a pneumatic signal and is commonly used in the automation industry. A commercially available conventional I/P-converter is shown in Figure 5.5 [92]. Figure 5.6a illustrates
5.2. MICROVALVE DESIGNS

Figure 5.5: A commercially available conventional I/P converter [92]. The inlet and outlet tube connector ports are at the bottom.

Figure 5.6: (a) Functional representation of a pressure-control element, and (b) a graph illustrating its pressure characteristics. The controller can operate between two pressures, $P_{\text{supply}}$ and $P_{\text{atm}}$. The dashed line in the plot indicates the ideal behavior, while the solid line indicates actual performance when two leaky valves are used [67]. $P$ represents the pressure and $\dot{m}$ the mass flow rate.

The working principle of a 3/2-way pressure controller, in which a high pressure source, $P_{\text{supply}}$, and a low pressure source, $P_{\text{atm}}$, are connected with two electrically controlled valves. In between the two valves, a pressure $P_{\text{work}}$ can be withdrawn. By controlling the two valves, the output pressure can be controlled. Figure 5.6b illustrates the dynamic pressure range $P_{\text{dyn}}$ of two leaky valves in series. Using two valves, each with a leak rate (closed-state flow relative to open-state flow) of 20%,
CHAPTER 5. MICROVALVES

Table 5.1: The three different gate valve configurations.

<table>
<thead>
<tr>
<th>Flow direction:</th>
<th>Gate movement:</th>
<th>Previous work:</th>
</tr>
</thead>
<tbody>
<tr>
<td>out of plane</td>
<td>in plane</td>
<td>[95–97]</td>
</tr>
<tr>
<td>in plane</td>
<td>in plane</td>
<td>[93,94]</td>
</tr>
<tr>
<td>in plane</td>
<td>out of plane</td>
<td>[44,67]</td>
</tr>
</tbody>
</table>

A pressure controller can be constructed with a dynamic pressure range of 94% of the full range [67].

Depending on the main flow and actuation direction, three fundamental gate valve configurations can be distinguished as shown in Table 5.1 [67]. Microvalves with in-plane movement and in-plane flow have only been demonstrated for liquid flow [93,94]. Microvalves with in-plane moving gates and out-of-plane flow have been demonstrated for gas control [95–97]. One well-known commercial valve is shown in Figure 5.7.

Figure 5.7: A schematic cross section (a) and wafer stack (b) of a commercially available pressure-balanced sliding-gate microvalve driven by thermal expansion and contraction of electrically conductive ribs [95,98,99].
5.3 DESIGN OF OUT-OF-PLANE GATE MICROVALVES

The design with in-plane flow and out-of-plane gate actuation is the most promising design for reducing the valve footprint area, since no extra footprint area is reserved for the gate movement. Gate valves with in-plane moving gates and actuators operating outside the chip surface area have not yet been reported in the literature, but could potentially also be used for the creation of valves with low footprint areas. This thesis concentrates on out-of-plane gate microvalves.

5.3 Design of out-of-plane gate microvalves

Previously, three different out-of-plane gate microvalve designs have been demonstrated and named after the location and movement of the gate and actuator relative to the flow orifice. The designs are the back-gate valve, the front-gate valve and the side-gate valve and are compared in Table 5.2 [67].

One of the most important factors when creating gate valves is to reduce the leakage gap between the gate and the orifice. The leakage gap in the front-gate design is limited by the gate movement, whereas in the back-gate and side-gate designs it is limited by the fabrication process alone. Fabrication of the valve is preferably carried out using Deep Reactive Ion Etching (DRIE) in silicon, since it allows high-aspect-ratio etching, i.e., large difference between the depth of the etch and size of the gap. A typical achievable DRIE aspect ratio is 30:1 [100], i.e., a 1 µm gap can be created with a depth of 30 µm. However, state-of-the-art DRIE

<table>
<thead>
<tr>
<th>Valve:</th>
<th>Illustration:</th>
<th>Advantages:</th>
<th>Disadvantages:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td><img src="image1.png" alt="Front Valve Illustration" /></td>
<td>Large leakage gap since the gate would otherwise touch the flow orifice.</td>
<td></td>
</tr>
<tr>
<td>Back</td>
<td><img src="image2.png" alt="Back Valve Illustration" /></td>
<td>Large footprint area when actuators and flow channel are parallel.</td>
<td></td>
</tr>
<tr>
<td>Side</td>
<td><img src="image3.png" alt="Side Valve Illustration" /></td>
<td>Small footprint. Gate orientation always orthogonal to the flow, resulting in no change in the static forces on the gate during actuator movement.</td>
<td>Torsional forces on the actuator. Part of the gate still blocks the flow orifice at full actuation. The substrate makes contact with the gate during opening.</td>
</tr>
</tbody>
</table>
machines can achieve aspect ratios of more than 100:1 [101], greatly decreasing the leakage flow of the valves.

All of the previously reported out-of-plane actuated gate microvalves have featured external actuation. Attempts with integrated thermal bimorph actuators failed since the actuators were not strong enough to withstand the vibrations and forces generated by the high flow or pressure of the gas medium [67]. For gas-microvalve applications, a robust actuator solution is therefore needed. SMAs should thus be ideal for gate microvalves since they can be used for the fabrication of robust large-deflecting actuators.

The following sections present design improvements to the three different out-of-plane gate microvalves and demonstrate actuation with SMAs, allowing the creation of small high-performance microvalves.

**Back-gate valve improvements**

The main disadvantage of the previous back-gate valve design is the large footprint needed since the two actuator beams are positioned on the side of the central flow channel (Table 5.2) [67]. The footprint can be decreased by relocating the actuator elements onto the roof of the flow channel, as illustrated in Figure 5.8. This new design, henceforth referred to as "Design A", results in a more compact microvalve with a highly optimized footprint area. A disadvantage of the relocation is that the valve actuator has to counteract part of the working pressure during closed-state operation, which limits the maximum operational pressure range. The inlet port can also be relocated to underneath the valve itself, potentially allowing easier assembly compared to the previous design.

The improved "Design A" back-gate valve has leakage out-of-plane (upwards) and in-plane (to both sides) in the closed state as illustrated in Figure 5.9. The back-gate valve can further be improved by creating an axially symmetric version, hereafter called "Design B", which eliminates the in-plane leakage flow as illustrated in Figure 5.8. The out-of-plane leakage gap can also be fabricated with smaller dimensions than the in-plane leakage gap since a lower etch depth is required. In addition, this design offers a larger orifice area and thereby potentially a larger

![Figure 5.8: Back-gate valve design improvements with an SMA actuator (Paper 6).](image-url)
5.3. DESIGN OF OUT-OF-PLANE GATE MICROVALVES

Both the improved Design A and Design B microvalves have been fabricated and are evaluated in Paper 6. The actuator chosen for these valve designs was a cold-rolled NiTi SMA-sheet actuator, which was integrated using Au-Si eutectic bonding as presented in Chapter 3.5. This actuator material is more rigid and better able to counteract large pressures and vibrations than the thermal bimorph actuators previously used [67].

In the chosen valve design, the drawbacks associated with part of the pressure drop being over the actuator is turned into an advantage. This pressure load on the actuator is used for valve opening, removing the need for integration of an additional SMA cold-state deformation mechanism, such as a stress layer, additional spring or displacement element, discussed in Chapter 4.5. The operational principle of the valve is illustrated in Figure 5.10 and corresponding SEM images of the valve in an open and closed state are shown in Figure 5.11.

The valve also demonstrated excellent performance. The results of electrically switching the valve are shown in Figure 5.12. The leakage was however relatively high in this design. The main reasons were insufficient heating of the actuator and deformation of the actuator due to the leak flow pressure. Paper 6 provides a detailed evaluation of the influence of parameters like leakage gap dimensions,
Figure 5.10: (a) 3D illustration of a Design A cantilever valve. (b) The inherent gate valve leakage flow is guided from the inlet, via a narrow leakage gap, to the area underneath the SMA actuator and then sideways around the SMA. The valve is opened by the pressure load $P_s - P_{out}$ on the SMA actuator. This pressure is only a fraction of the inlet-outlet pressure drop. (c) When the SMA actuator is heated, the pressure load is counteracted by the SMA shape recovery and the valve closes (Paper 6).

Figure 5.11: SEM images of a Design A SMA back-gate valve in an open and closed state, respectively (Paper 6).

actuator length and orifice dimension, and suggests several ways to improve this valve further. The paper also presents an evaluation of Design B valves. Since the Design B actuator was relatively weak, the leakage of the valve was very high. Modifications to the actuator design, may help to improve the efficacy of this type of valve.
5.3. DESIGN OF OUT-OF-PLANE GATE MICROVALVES

Front-gate valve improvements

The major drawback of the original front-gate valve by Haasl et al. was the large leakage gap needed between the flow orifice and the gate to prevent the gate from hitting the orifice since the gate rotates towards the orifice while opening, as illustrated in Figure 5.13a. This problem can be eliminated by changing the gate movement to be in the opposite direction so that the gate moves away from the orifice, as shown in Figure 5.13b.

An ideal actuator for this improved valve design is the SMA-wire actuator presented in Chapter 4.6. The design for an SMA-wire actuated gate valve is depicted in Figure 5.14 together with a photograph of a prototype valve. The valve successfully controlled a gas flow of 1600 sccm at 200 kPa pressure drop and an actuation power of less than 90 mW. An actuation frequency of greater than 10 Hz

![Figure 5.12: Electrical valve switching with 0.35 W input power at different actuation frequencies (Paper 6).](image)

![Figure 5.13: Illustration of working principle of (a) the original Haasl front-gate valve and (b) the improved front-gate valve design where the gate moves in the opposite direction, not hitting the flow channel (Paper 7).](image)
Figure 5.14: Illustration of an SMA wire front-gate valve in the close (a) and open state (b) and a photograph of a fabricated microvalve from the top (c) (Paper 7).

Figure 5.15: Flow rate and gate deflection vs. time for an SMA-wire valve actuated at 1 Hz, 2 Hz, 6 Hz and 10 Hz, respectively. The inlet relative pressure was kept constant at 200 kPa (Paper 7).

is achievable because the gas flow actively cools the SMA wires. Figure 5.15 shows the flow rate and actuator deflection with 1, 2, 6 and 10 Hz actuation.

However, the closed-state leakage of the valve was very high. This is due to the SMA-wire actuator having a large cold-state deflection and the first prototype having a large leakage gap since the valve was fabricated with fast prototyping in mind, and thus limited mask resolution. The flow rate control can be greatly increased and the leakage decreased with small design improvements and higher resolution fabrication techniques, respectively. This valve is presented in detail in Paper 7.
5.4. VALVE PACKAGING

Side-gate valve improvements

Improvements to the side-gate valve are also feasible. A major drawback of the design proposed by Haasl et al. is the torsional forces acting on the actuator. A possible solution to this is a pressure-balanced side-gate valve. A suggested design of such a valve with SMA-wire actuation, is illustrated in Figure 5.16.

![Illustration of a pressure-balanced side-gate valve with an integrated SMA-wire actuator.](image)

The actuation is performed by two SMA wires on top of the valve together with cold-state reset beams placed on each side of the gates. The flow direction is from underneath the valve and then out at both sides. It is expected that this design will be characterized by low leakage flows in the cold state since the gate ends below the orifice bottom. The second disadvantage of the side-gate valve of Haasl et al. is the gate hits the underlying substrate. The length of the gate in the above design can be shortened to avoid this problem or the substrate underneath does not need to be in direct contact with the bottom of the gate.

This design can be developed to create a high-performance SMA-wire valve, but the project has not yet started.

5.4 Valve packaging

To create a microvalve for commercial use, the packaging of the valve is important. For the microvalves presented, packaging options include wafer-level packaging, using wafer-bonding techniques prior to dicing the wafer, and after dicing solder it to a printed circuit board (PCB) or mounting the valve chip directly in a TO-8 housing. Packaging in TO-8 housings is standardized for MEMS pressure sensors.
An example of an SMA-sheet microvalve that is glue mounted into a modified commercially available TO-8 metal package for pressure sensors is displayed in Figure 5.17.

5.5 Valve comparison

For a gas microvalve to be attractive for practical applications, the following aspects are of importance: (1) The valve should control high flows; (2) The valve should have low manufacturing cost, which can be achieved by having a small footprint area and employing batch manufacturing; (3) The power consumption should be low to enable the valve to be used in embedded systems and to fully exploit the size reduction with respect to standardized valves; (4) The valve should be able to operate under high pressures; (5) The valve should have low leakage flows; (6) The valve should be able to switch between states at a relatively high frequency. Since some of these aspects are contradictory, the ideal valve is difficult to build, and the most important factors for the intended application need to be chosen. An appropriate measure to compare different types of microvalves is needed. For I/P converters, the most important properties are high-flow control and low manufacturing costs. Since the flow rate is dependent on the pressure drop over the valve and the size of the microvalve, one relevant measure is therefore the pneumatic performance per cost, $\nu$, which is here defined as the flow rate control, $Q_{\text{open}} - Q_{\text{close}}$, per pressure drop, $P_{\text{in}} - P_{\text{out}}$, divided by the batch-manufacturable MEMS footprint area of the valve, $A_v$:

$$\nu = \frac{Q_{\text{open}} - Q_{\text{close}}}{A_v(P_{\text{in}} - P_{\text{out}})}$$  \hspace{1cm} (5.1)
The performance per footprint of several state-of-the-art microvalves is compared in Table 5.3 together with other important properties for microvalves.

Since the flow rate is not linearly related to the pressure drop over the valve, it is also interesting to study the flow rate control/footprint area of the valve for different pressures. Figure 5.18a shows a plot of these quantities for the best-performing valves with integrated actuation together with a theoretical optimized model of an SMA-wire valve. It is also interesting to compare the flow rate control relative to the actuation power for these valves, which is plotted in Figure 5.18b.

From the Table 5.3 and Figure 5.18, it is clear that gate valves are superior to traditional seat-valve designs when it comes to high-flow control relative to both footprint area and power. The SMA-sheet back-gate valve exhibits a three times higher performance per footprint than any other gas microvalve, mainly because of its small size.

The prototype SMA-wire valve is comparable to previous gate microvalves, but the theoretical model predicts that the SMA-wire valve can achieve a performance similar to an SMA-sheet valve. The SMA-wire valve also offers the lowest power consumption per flow rate control when compared with existing microvalves. The power is more than one order of magnitude lower than for the in-plane actuated gate valves [95,96]. Only for PZT (lead-zirconate-titanate) piezoelectric and electrostatic seat microvalves the power is lower, but the flow rate control is also much lower and the operational voltage is two orders of magnitude higher [85,87,89,103].

The main drawback of the SMA microvalves presented in this thesis is the relatively high leakage, but solutions to this are discussed in detail in Paper 6 and 7.

Figure 5.18: Comparison of the microvalves in presented in this thesis to previous work, showing plots of (a) controllable flow rate/footprint area as function of pressure, and (b) controllable flow rate/power (Papers 6 and 7).
Table 5.3: Comparison of valve performance of gate and seat microvalves with high performance or SMA actuation

<table>
<thead>
<tr>
<th>Design and type</th>
<th>Footprint area (mm x mm)</th>
<th>Max control flow rate (sccm)</th>
<th>Max pressure drop (kPa)</th>
<th>Max relative ν %</th>
<th>Indicative leakage</th>
<th>Input power (W)</th>
<th>Input voltage (V)</th>
<th>Response time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gate microvalves</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thesis Paper 6 (out-of-plane gate, SMA sheet)</td>
<td>1 x 3.3</td>
<td>4000</td>
<td>200</td>
<td>100%</td>
<td>10%-30%</td>
<td>350 mW</td>
<td>1 V</td>
<td>300 ms</td>
</tr>
<tr>
<td>Walters et al. (in-plane gate, integrated thermal) [96]</td>
<td>4 x 4</td>
<td>5000</td>
<td>138</td>
<td>33.75%</td>
<td>6%-10%</td>
<td>1.1 W</td>
<td>30 V</td>
<td>50 ms</td>
</tr>
<tr>
<td>Haasl et al. (out-of-plane gate, external actuation) [67]</td>
<td>2.3 x 3.7</td>
<td>3400</td>
<td>95</td>
<td>31.34%</td>
<td>30%</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Thesis Paper 6 (circular out-of-plane gate, SMA sheet)</td>
<td>6 x 6</td>
<td>850</td>
<td>8</td>
<td>21.99%</td>
<td>30%-50%</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Thesis Paper 7 (out-of-plane gate, SMA wire)</td>
<td>5 x 1.6</td>
<td>1600</td>
<td>200</td>
<td>13.04%</td>
<td>50%-70%</td>
<td>90 mW</td>
<td>0.6 V</td>
<td>50 ms</td>
</tr>
<tr>
<td>Williams et al. (in-plane gate, integrated thermal) [95]</td>
<td>2.5 x 5.0</td>
<td>4000</td>
<td>500</td>
<td>10.73%</td>
<td>∼0%</td>
<td>1.4 W</td>
<td>20 V</td>
<td>500 ms</td>
</tr>
<tr>
<td>Luharuka et al. (in-plane gate, external magnetic) [97]</td>
<td>5 x 5</td>
<td>500</td>
<td>69</td>
<td>3.63%</td>
<td>2%-25%</td>
<td>“few mJ”</td>
<td>n/a</td>
<td>10 ms</td>
</tr>
<tr>
<td><strong>High performance seat microvalves</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zdeblick et al. (best seat valve, phase change) [104]</td>
<td>6.3 x 6.6</td>
<td>5000</td>
<td>690</td>
<td>6.40%</td>
<td>0%</td>
<td>0.8 W</td>
<td>15 V</td>
<td>n/a</td>
</tr>
<tr>
<td>Park et al. (PZT) [89]</td>
<td>10 x 10</td>
<td>1000</td>
<td>55</td>
<td>1.85%</td>
<td>0%</td>
<td>0.16 µW</td>
<td>60 V</td>
<td>0.7 ms</td>
</tr>
<tr>
<td>Wu et al. (PZT) [103]</td>
<td>6 x 9</td>
<td>800</td>
<td>100</td>
<td>1.60%</td>
<td>0%</td>
<td>n/a</td>
<td>150 V</td>
<td>30 ms</td>
</tr>
<tr>
<td>Barth et al. (Bistable SMA, including full package) [86]</td>
<td>11 x 6</td>
<td>2200</td>
<td>300</td>
<td>0.90%</td>
<td>0%</td>
<td>∼0.3 W</td>
<td>n/a</td>
<td>30 ms</td>
</tr>
<tr>
<td>NiTi Alloy company (SMA) [68]</td>
<td>8.0 x 5.0</td>
<td>1000</td>
<td>690</td>
<td>0.90%</td>
<td>0%</td>
<td>200 mW</td>
<td>2 V</td>
<td>15 ms</td>
</tr>
<tr>
<td>Huff et al. (electrostatic pressure balanced) [87]</td>
<td>3.6 x 3.6</td>
<td>550</td>
<td>552</td>
<td>0.76%</td>
<td>0%</td>
<td>n/a</td>
<td>200 V</td>
<td>n/a</td>
</tr>
</tbody>
</table>

*Note: Values represent the pneumatic performance/footprint (height x width) where possible. The footprint was determined as the height-manufacturable part of the valve, not including housing where possible. Inclined valves are indicated by the symbol ‘\( \ldots \)’.
5.6 Discussion and outlook

Gate microvalves are very interesting for high-gas-flow applications, and both the SMA-sheet valves and SMA-wire valves are promising designs. The SMA-sheet microvalve displays the highest flow rate control/footprint area since the actuator is located on top of the flow channel, resulting in no wasted space. The SMA-wire actuator can be optimized in the same way by placing the SMA-wire actuator on top of a wafer stack with a flow channel. However, the cost savings of making this change are questionable.

Since the SMA-sheet valve operates in bending mode, and most of the bending occurs at the base when the gas pressure opens the valve, it is less efficient than the SMA-wire valve, which operates under pure tension of the wires. By using stress-layer deposition on the SMA sheet for the cold-state deflection, uniform bending can be achieved and a larger part of the SMA can be utilized. However, this would make the fabrication more complex compared to using the gas pressure to open the valve.

For microvalve applications demanding low-power and low-voltage actuation, the SMA-wire valve demonstrated excellent flow rate control when actuated with direct Joule heating of the wires.

The main concern with both types of SMA valves is still the relatively high leakage. However, the leakage can potentially be lowered to less than 10% with the design improvements suggested in the papers.

The best-performing SMA-sheet valve can potentially be further optimized to increase the flow rate control/footprint area by an additional factor of four. This can be achieved by extending the gate in an SMA-sheet back-gate valve to both sides of the valve channel (similar to a combination of a back-gate valve and a side-gate valve) and shortening the actuator to 2.25 mm (as described in Paper 6), and thereby decreasing the leakage to less than 5%. As described in Paper 7 the SMA-wire valve prototype can be improved by a factor of six with relatively easy methods, and a further doubling of the flow rate control/footprint area is possible if the outlet port is relocated to the bottom instead of the top, thus avoiding the space between the two silicon cantilever arms. The actuation frequency would however be lowered in this case since the active cooling will be less. It is also feasible to improve the gate valves with alternative designs, as for example, the pressure-balanced side-gate valve.

The next generation of valve designs should focus on a fully packaged valve, preferably with packaging on wafer-level. The valve should also be manufactured with a direct application approach and allow multiple microvalves to be easily connected in series, for example, to be used as a 3/2 way valve for I/P converters.

For an I/P converter valve, it may be possible to create a valve with one inlet port and two outlet ports, where the ports are controlled by one actuator, e.g., the high-pressure inlet port is closed while the low-pressure outlet port is opened by the actuator.
Chapter 6

Conclusions

This thesis presents methods for fabricating MEMS actuators and high-flow gas microvalves using wafer-level integration of nickel-titanium shape memory alloys in the form of wires and sheets.

For SMA sheets, wafer-level Au-Si eutectic bonding has been presented as a useful SMA-integration method. A high yield and strong bond can be achieved by first patterning the SMA sheet and then bonding only small areas combined with having a relatively thick gold layer.

For SMA wires, both manual and wire-bonder-assisted alignment and placement of NiTi wires on wafer-level have been successfully demonstrated. Methods for polymer fixing, Ni electroplating fixing and mechanical silicon clamping of the wires have been shown. Ni electroplating offers the most-promising permanent fixing technique on a chip-level since both a strong mechanical and good electrical connection to the wire are achieved in the same process step and the occupied footprint area of the fixture is low.

By integrating prestrained SMA wires on silicon cantilevers and fixing them by Ni electroplating, resistively heated microactuators have been fabricated. These actuators demonstrate deflections that are among the highest reported for microactuators. The actuators also feature a relatively low power consumption and high reliability during long-term cycling.

A method for selectively releasing Au-Si eutectically bonded microstructures by electrochemical etching has also been presented. For complex 3D microsystems, this method allows release and movement of microstructures after being bonded during the fabrication.

New designs for gas-flow-control microvalves have been presented and prototypes have been built that use both SMA sheets and SMA wires for actuation. The SMA sheet microvalve exhibited a record pneumatic performance per footprint area. The SMA wire actuated microvalve also demonstrated high flow rate control but in addition, offered benefits of low-voltage actuation and low overall power consumption. This thesis has demonstrated gate microvalves with a flow rate
control per footprint area three times higher than previously reported. In addition, the highest flow rate control per power consumption was more than twice that obtained in previous work. Design improvements for further improving the flow control have also been presented.

Large-deflecting SMA actuators and gas-flow-control gate microvalves both have a bright future in MEMS, and there is also scope for further enhancements in upcoming research.

The next research targets for fabrication of efficient SMA sheet actuators should be to combine cold-state resets mechanisms, such as stress layers and mechanical obstructions, with integrated heaters. In addition, electroplate fixing of SMA sheets, similar to SMA-wire fixing techniques, would be interesting to investigate further. Regarding SMA wires, the next step is to further automate the integration process with wire bonders. Future work on the next generation SMA valves should aim to develop techniques to reduce the leak flow, as mentioned in this thesis, and fabricate a fully packaged valve.
Summary of Appended Papers

**Paper 1:** *Localized removal of the Au-Si eutectic bonding layer for the selective release of microstructures*

This paper presents and investigates a novel technique for the footprint and thickness-independent selective release of Au-Si eutectically bonded microstructures through the localized removal of their eutectic bond interface. The technique is based on electrochemical removal of the gold in the eutectic layer and selectivity is achieved by patterning the eutectic layer and ensuring proper electrical connection or isolation of the areas to be etched or kept, respectively. The gold removal results in a porous silicon layer, which exhibits similar behavior to standard etch holes during subsequent sacrificial-release etching. The paper presents the principle and design requirements of the technique. First, test devices were fabricated and the method successfully demonstrated. The paper also describes an investigation of the release mechanism and the effects of different gold layouts on both the eutectic bonding and the release procedure.

**Paper 2:** *Wafer-level integration of NiTi Shape Memory Alloy on silicon using Au-Si eutectic bonding*

This paper reports on the wafer-level integration of shape memory alloy sheets to silicon substrates through Au-Si eutectic bonding. Different bond parameters, such as Au-layer thickness and substrate surface treatment were evaluated. The amount of gold in the bond interface was found to be the most important parameter governing a high bond yield. The gold amount can be determined by the barrier layers between the Au and Si or by the amount of Au deposition. To reduce the stresses created from the thermal mismatch between Si and NiTi, patterning of the SMA sheet and bonding of only small areas is also crucial. With a gold layer thickness of 1 µm and bond areas ranging from $200 \times 200 \text{ µm}^2$ to $800 \times 800 \text{ µm}^2$, a high bond strength and yield above 90% was demonstrated.
Paper 3: Design and wafer-level fabrication of SMA wire microactuators on silicon

This paper reports on the fabrication of microactuators by wafer-level integration of prestrained shape memory alloy wires to silicon structures. The wires were strained under pure tension, and the cold-state reset was provided by single-crystalline silicon cantilevers. A mathematical model is discussed, which provides a useful approximation for practical designs and allows the performance of the actuators to be analyzed. Prototypes were fabricated, tested and experimentally evaluated. The test results were in close agreement with the calculated values, and they show that the actuators can achieve displacements that are among the highest reported.

Paper 4: Robust actuation of silicon MEMS using SMA wires integrated at wafer-level by nickel electroplating

This paper reports on both the wafer-level fixation and electrical connection of prestrained SMA wires to silicon MEMS using electroplating, and the fabrication of the first Joule-heated SMA-wire actuators on silicon. The proposed integration method provides both high bond strength and electrical connections in the same processing step, and it allows mass production of microactuators with a high work density. SEM observation revealed an intimate interconnection between the SMA wires and the silicon substrate. The variation of the actuators’ performance across the wafer was evaluated on three $4.5 \times 1.8 \, \text{mm}^2$ footprint devices, demonstrating reproducible results. The actuators exhibited a mean hot-state deflection of $536 \, \mu\text{m}$ and a mean stroke of $354 \, \mu\text{m}$ with a low power consumption (less than $70 \, \text{mW}$). One actuator was tested for $150 \times 10^3$ cycles, and it demonstrated a highly reliable long-term performance, showing neither material degradation nor failure of the nickel anchors.

Paper 5: Wire-bonder-assisted integration of non-bondable SMA wires into MEMS substrates

This paper reports on a novel technique for the integration of NiTi shape memory alloy (SMA) wires and other non-bondable wire materials into silicon-based MEMS structures using a standard wire-bonding tool. The efficient placement and alignment functions of the wire-bonding tool were used to mechanically attach the wire to deep-etched silicon anchoring and clamping structures. This approach enables reliable and accurate integration of wire materials that cannot be wire bonded by traditional means.
Paper 6: SMA microvalves for very large gas flow control manufactured using wafer-level eutectic bonding

This paper presents a novel gas microvalve design concept, in which a flow control gate is opened by pneumatic pressure and closed by an SMA actuator, allowing large-flow control. Two different design variations were fabricated using a wafer-level Au-Si eutectic bonding process for TiNi to silicon integration. The resulting microvalves demonstrated the highest reported pneumatic performance per footprint area: a microvalve with a footprint of only $1 \times 3.3 \text{ mm}^2$ was able to successfully control a flow difference of 3100 sccm at a pressure drop of 70 kPa using a power of 0.35 W.

Paper 7: A low power high flow SMA wire gas microvalve

In the work described in this paper, the use of SMA-wire actuators for high-gas-flow control was investigated. A theoretical model for effective gas-flow control was developed and gate microvalves prototypes were fabricated. Even though the first prototypes displayed high leakage, the SMA-wire actuator demonstrates robust control of flow rates of more than 1600 sccm at a pressure drop of 200 kPa. The valve could be switched at frequencies of over 10 Hz with an actuation power of 90 mW. Compared to the current state-of-the-art high-flow microvalves, the proposed design offers advantages of a low-voltage actuator with low overall power consumption. SMA-wire actuators are therefore well suited for high-pressure high-flow applications.
Acknowledgments

First of all, I would like to thank my principal supervisor Göran Stemme and my supervisor Wouter van der Wijngaart for taking me on as a PhD student and the guidance throughout the years. Göran for his great knowledge in the field of MEMS - he always knows what questions will be asked at conferences and by reviewers in advance. Wouter, for his crazy ideas and unconventional non-obvious ways of solving problems and for pushing me forward through the PhD.

A large contribution to the success of my PhD was the help and idea discussions with my roommate and coworker in the early years, Stefan Braun. Many of the initial ideas and solutions for the papers sprung from these discussions.

Also, many thanks to my coworker and SMA expert Donato Clausi at the Katholieke Universiteit Leuven in Belgium. We have had a good collaboration and Donato always provided great hospitality when I was visiting Leuven. During proofreading, Donato hopefully corrected all the errors in this thesis about SMAs.

I would also like to thank my other coauthors: Frank Niklaus for many discussions on wafer-level integration and bonding, Andreas Fischer for vast knowledge of wirebonders, Stephan Schröder for the thorough SMA-wire-bonding testing, Sobia Bushra for the extensive analysis of SMA eutectic bonding and Jan Peirs for the creative solution suggestions in the papers. In addition, many thanks to Kjell Norén for delivering better mechanical and electrical platforms than you actually ask for and without any restrictions. Many thanks also to the clean-room staff, especially Magnus Lindberg for repairing all damaged tools fast and efficiently.

My main thanks go to all the colleagues at MST for the nice, fun and pleasant atmosphere at the department during the years and also many fruitful discussions on non-MEMS topics. Thanks to all current and past colleagues: Adit, Andreas, Björn, Erika, Farizah, Frank, Gaspard, Göran, Hans, Hithesh, Joachim, Fredrik C, Fredrik F, Fritzi, Kjell, Kristinn, Martin, Niclas, Niklas, Nutapong, Mikael A, Mikael K, Mikael S, Sergey, Staffan, Simon, Stefan B, Stephan S, Thomas, Tommy, Umer, Valentine, Wouter and Zargham.

Also thanks to the people accidently left out above and feeling missing from this acknowledgment.

Last, but not least, the compulsory financial support acknowledgment to the Q2M project (Batch integration of high quality materials for microsystems), which received research funding from the European Commission through the
sixth framework program, and the European Research Council (ERC) through the Advanced Grant (267528): Towards Cost-Efficient Flexible Heterogeneous Integration for Micro- and Nanosystem Fabrication, both of which helped to fund my salary to play around with expensive equipment for the creation of the future technologies described in this thesis.

Also thanks to my girlfriend Maria, my family and my friends for their support during the PhD.
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Paper Reprints
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IOP Journal of Micromechanics and Microengineering, submitted April 2012
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Paper 5

Wire-bonder-assisted integration of non-bondable SMA wires into MEMS substrates

Andreas C. Fischer, Henrik Gradin, Stephan Schröder, Stefan Braun, Göran Stemme, Wouter van der Wijngaart and Frank Niklaus

Paper 6

SMA microvalves for very large gas flow control manufactured using wafer-level eutectic bonding

Henrik Gradin, Stefan Braun, Göran Stemme and Wouter van der Wijngaart

Paper 7

A low power high flow SMA wire gas microvalve

Henrik Gradin, Donato Clausi, Stefan Braun, Göran Stemme, Jan Peirs, Wouter van der Wijngaart and Dominiek Reynaerts

IOP Journal of Micromechanics and Microengineering, accepted for publication
Heterogeneous Integration of Shape Memory Alloys for High-Performance Microvalves

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Doctoral Thesis in Microsystem Technology
Stockholm, Sweden 2012